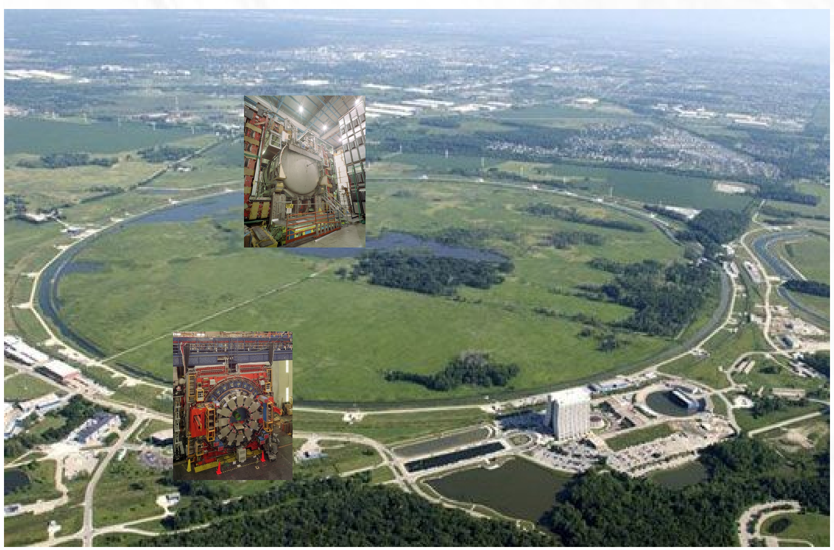
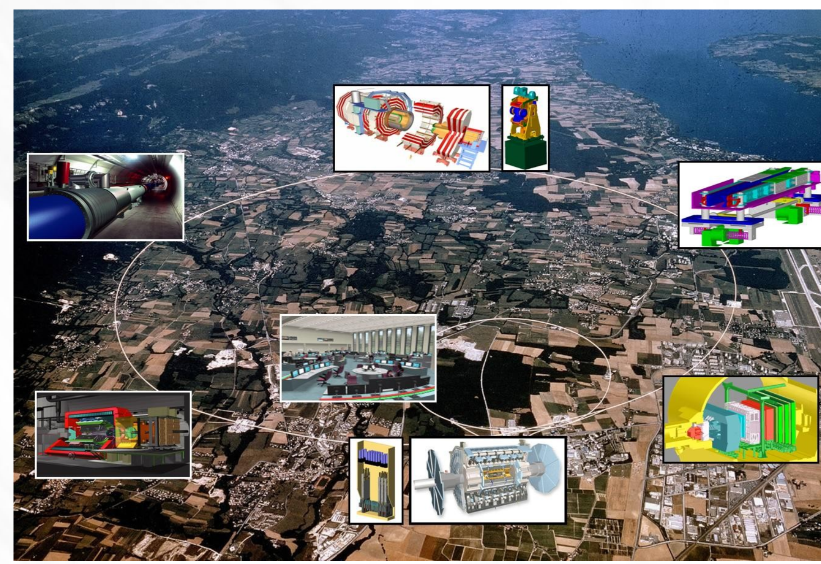
ELECTROWEAK PHYSICS
at
THE TEVATRON AND LHC

John Freeman
Fermi National Accelerator Laboratory





Unification

ELECTRO-

γ (massless)

+

WEAK

$W^{\pm}$ (80.4 GeV/c^2)
Z (90.1 GeV/c^2)

- Electromagnetic and weak forces unified by
  - Very high temperatures
  - Very smart theorists

  Weinberg, Glashow, Salam (1960's)

Weinberg, "A Model of Leptons"
Phys. Rev. Lett. 19:1264-1266, 1967
→ 7080 total citations!!

Split occurs at a sweltering

$$O\left(\frac{M_{W/Z}}{K_B}\right) \sim 10^{15} K$$

1 trillionth of a second after the Big Bang

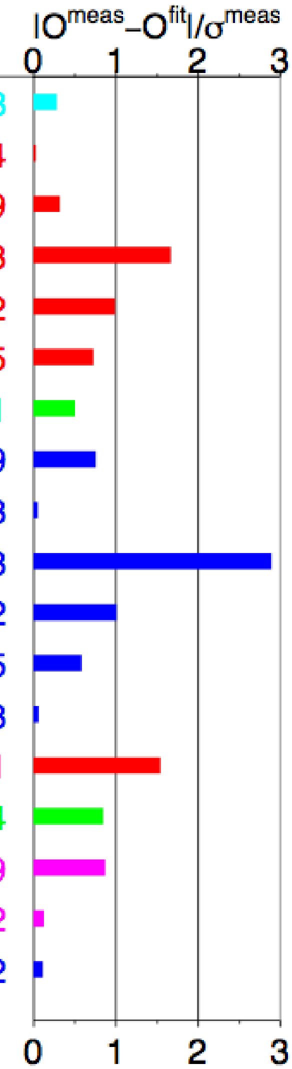
$K_B \rightarrow$ Boltzmann's constant

Verification

Gargamelle, CERN, 1973
→ neutral particle (Z)

UA1+UA2, SPS, CERN 1983
→ W, Z discovery

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

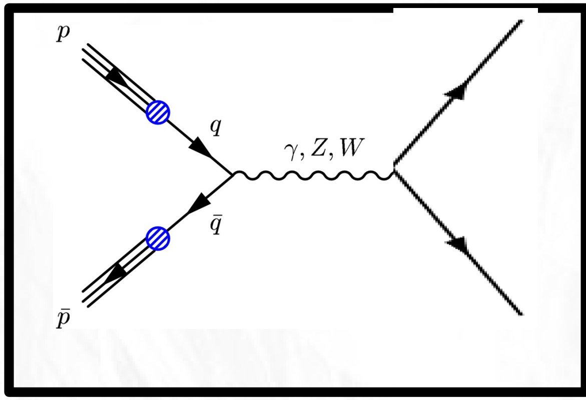


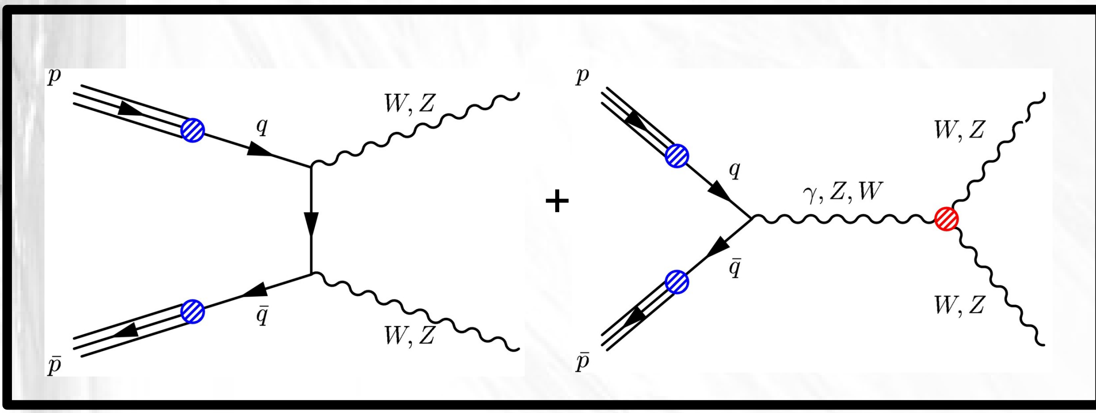
August 2009

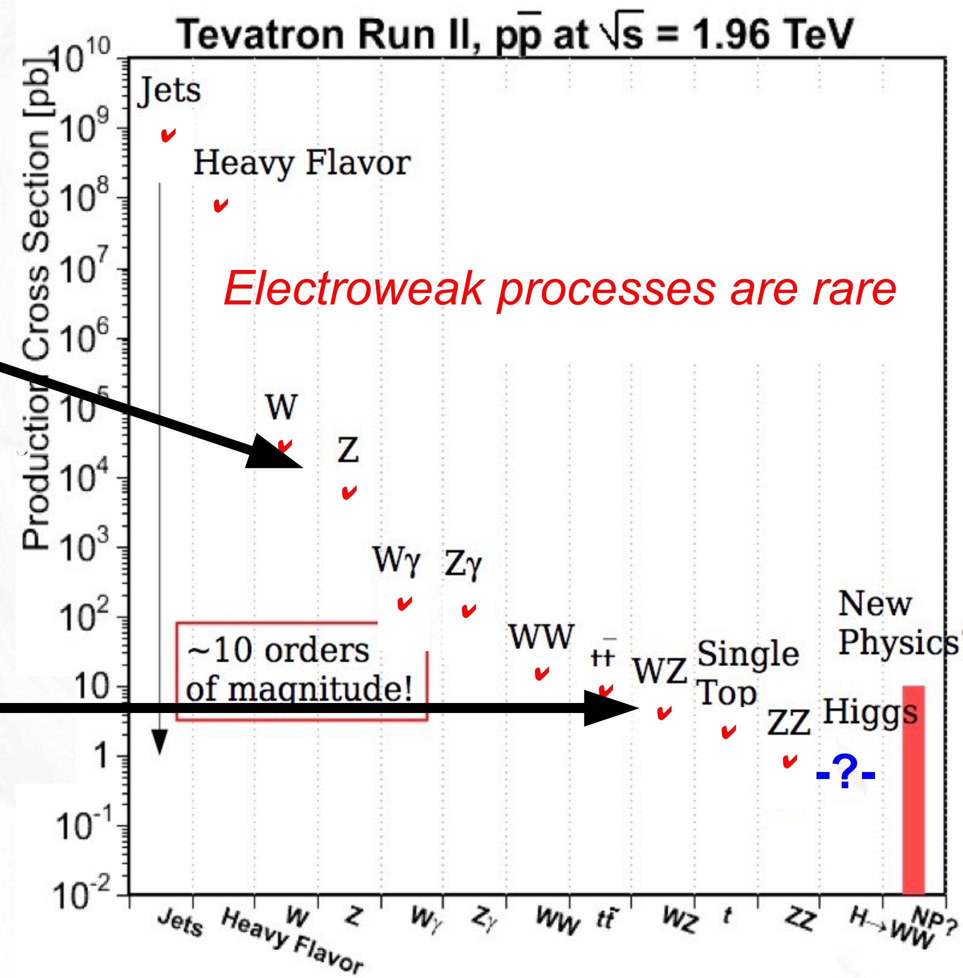
Perform overconstrained fit to the SM!

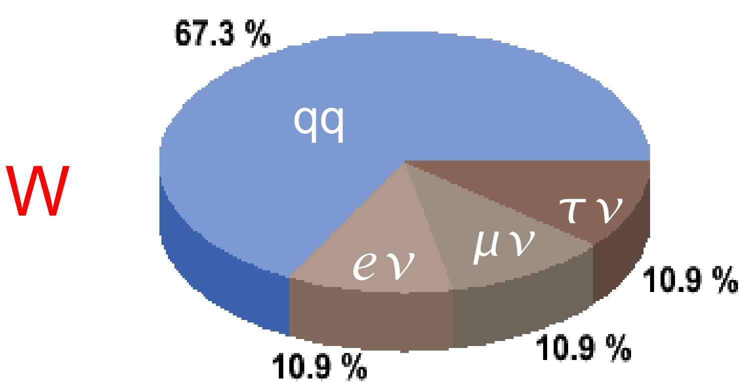
$$\rightarrow M_H = 87^{+35}_{-26}\, GeV/c^2$$

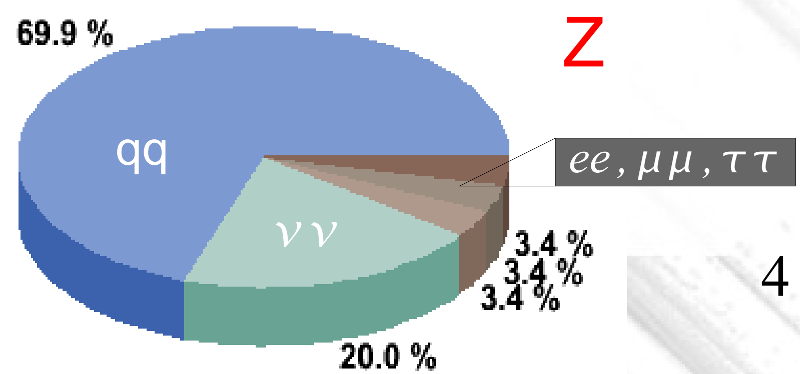
Electroweak Production



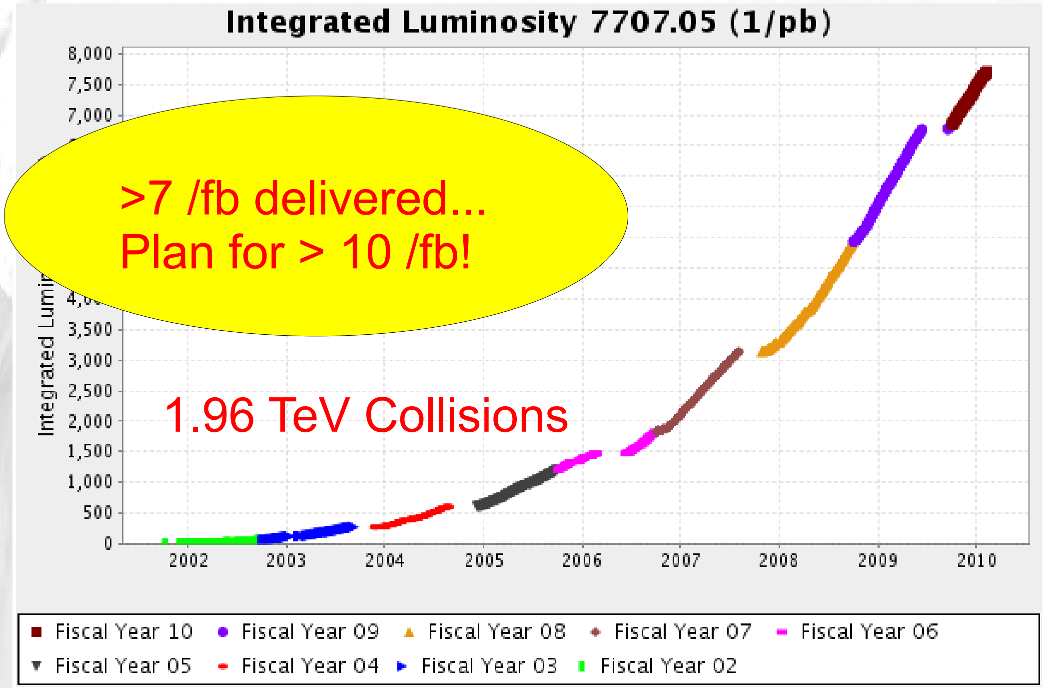








The LHC “vs” the Tevatron



LHC PLAN

- 2010: ~100 /pb @ 7 TeV
- 2011: ~1 /fb @ 7 TeV
- 2012: Shutdown
- *2013-20xx:*
  goal is 10s of /fb at 14 TeV!

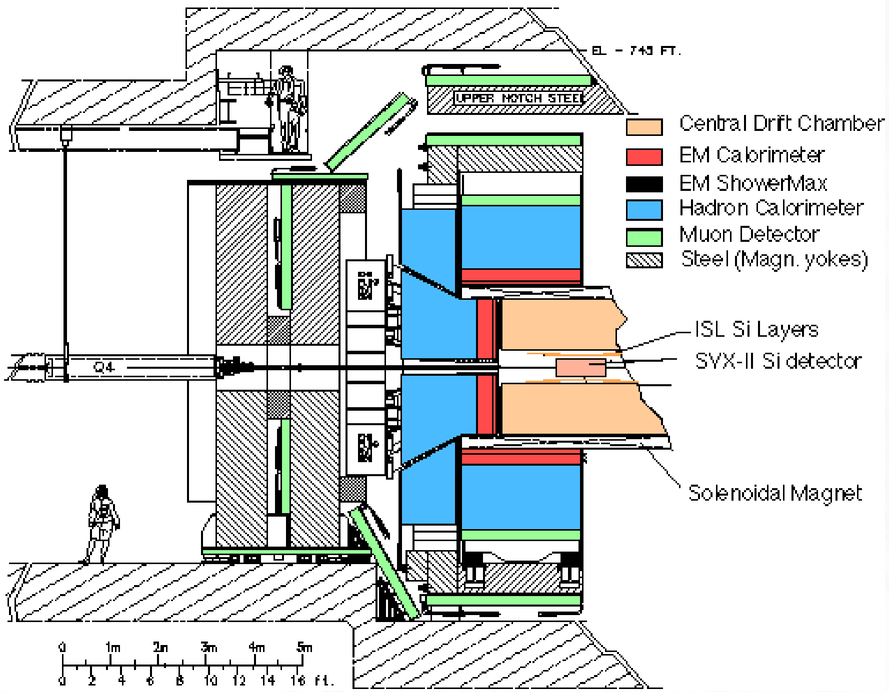
PROCESS	~ evts/fb (Tevatron)	~ evts/fb (LHC@14 TeV)
W	25M	180M
Z	7.5M	60M
WW	12.4k	111.6k
WZ	3.7k	47.8k
ZZ	1.43k	14.8k
W γ	19.3k	451k
Z γ	4.74k	219k

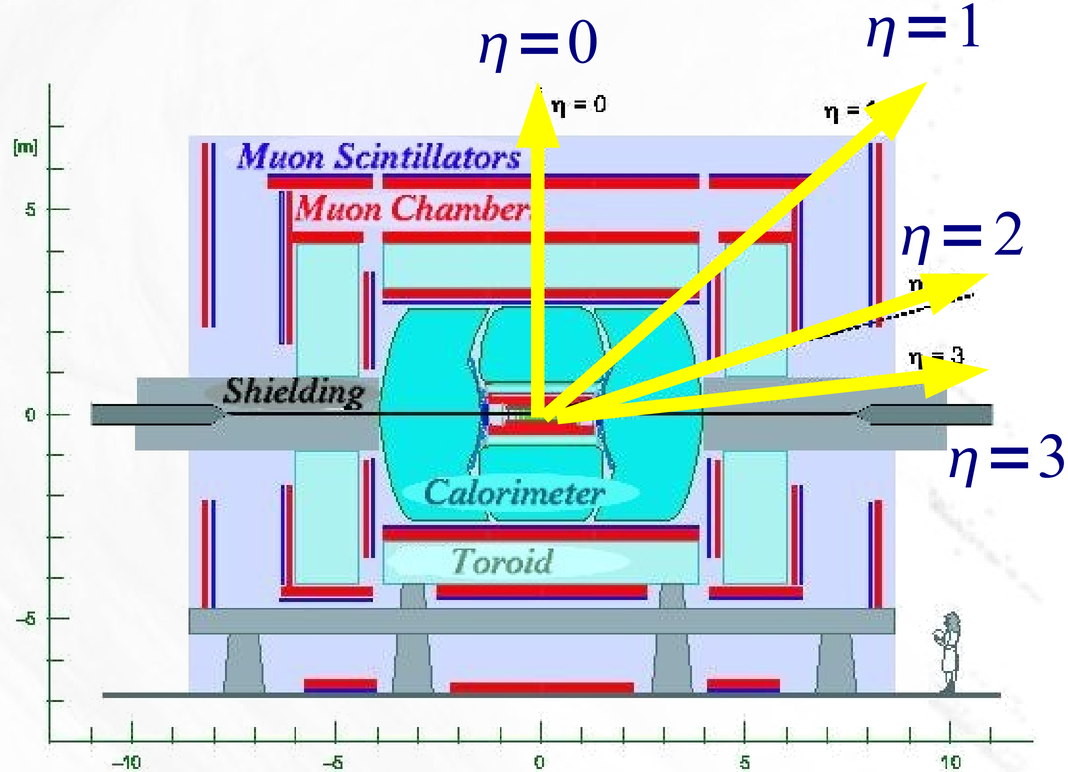
1 /fb = 1000 /pb , a unit of the number of particle collisions

-LHC will bring massive statistics!

→ ~10x higher production rate per collision (assuming 14 TeV)
→ 10-100x more data

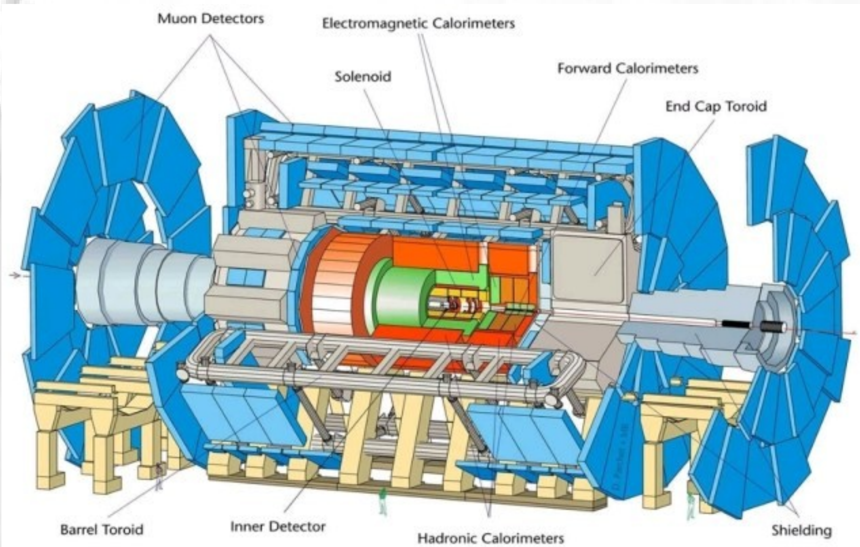
Tevatron: CDF and D0

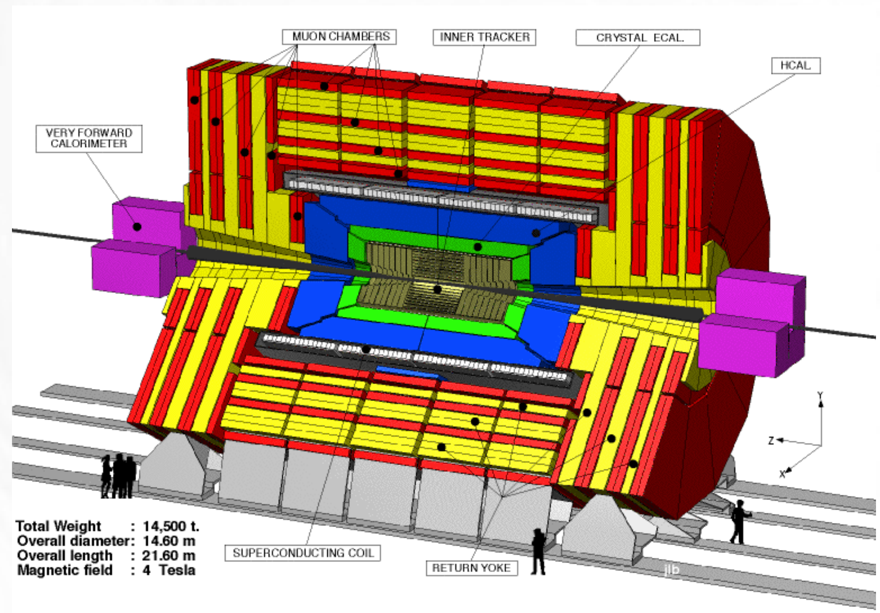




	CDF	D0
Tracker Coverage	$\|\eta\| < 2$	$\|\eta\| < 3$
Tracker Resolution (%)	$0.1\ P_T$	$0.14\ P_T \oplus 1.5$
Emcal Coverage	$\|\eta\| < 3.6$	$\|\eta\| < 4.2$
Emcal Resolution (%)	$13.7/\sqrt{E_T} \oplus 1\text{-}2$	$20/\sqrt{E} \oplus 2$
Muon Coverage	$\|\eta\| < 1.5$	$\|\eta\| < 2$

LHC: ATLAS and CMS





	ATLAS	CMS
Tracker Coverage	$\|\eta\| < 2.5$	$\|\eta\| < 2.6$
Tracker Resolution (%)	$0.034\ P_T \oplus 1.5$	$0.015\, P_T \oplus 0.5$
Emcal Coverage	$\|\eta\| < 4.9$	$\|\eta\| < 4.9$
Emcal Resolution (%)	$10/\sqrt{E} \oplus 0.2$	$3/\sqrt{E} \oplus 0.5$
Muon Coverage	$\|\eta\| < 2.7$	$\|\eta\| < 2.6$

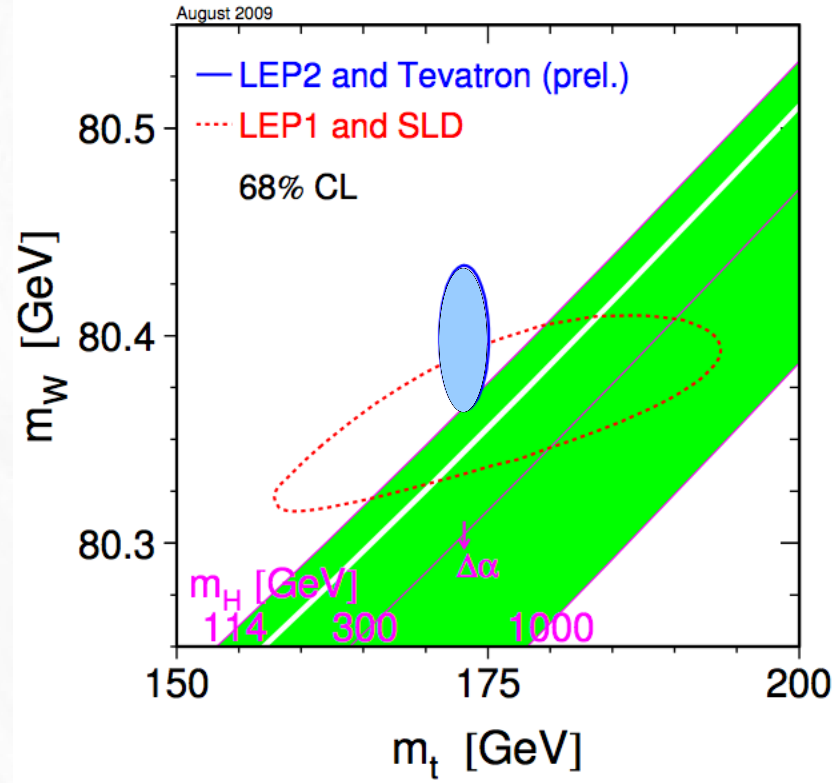
The W Mass

M_{top} = 173.1 +/- 1.3 GeV/ c^2

M_W = 80.399 +/- 0.023 GeV/ c^2

hep-ex/0903.2503v1

top quark, W, Higgs all interact

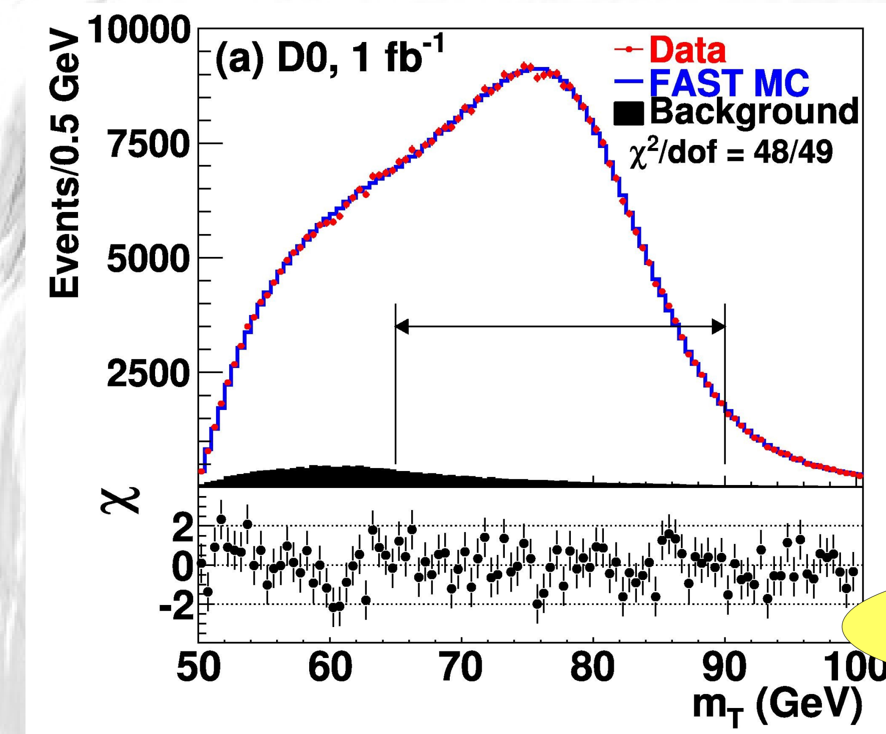


- Hold M_H fixed:

$$\Delta M_{top} = \underbrace{1.3\, GeV/c^2}_{1\sigma_{top}} \rightarrow \Delta M_W = \underbrace{8\, MeV/c^2}_{0.3\sigma_W}$$

Improving W mass measurement crucial for improved Higgs mass constraint!

Best W Mass Measurement



Error Type	MeV
Statistical	21
e energy scale	34
e energy resolution	2
e shower model	4
e energy loss model	4
Recoil model	6
e efficiencies	5
Backgrounds	2
PDFs	10
QED	7
W Pt	2

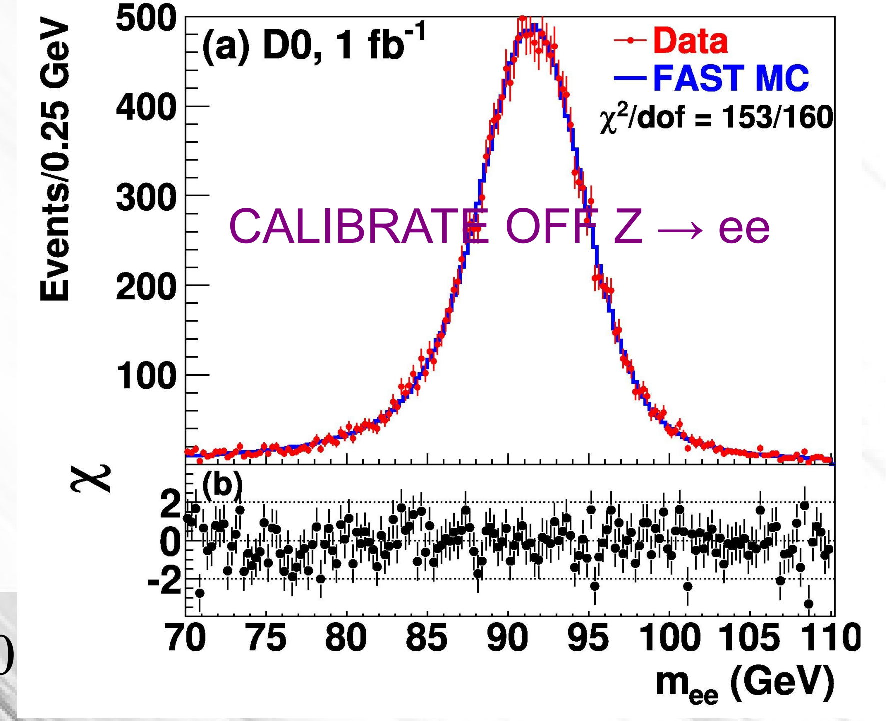
Detector systematics scale with Z statistics

Theory systematics do not!

$$M_W = 80.401 \pm 0.043\, MeV$$

$$m_T^W \equiv \sqrt{2 p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$ = "transverse mass"

- 499830 $W \rightarrow e\nu$ candidate events
  - $50 < m_T < 200$ GeV
  - Electron E_T, E_{Tmiss} > 25 GeV
  - Recoil energy < 15 GeV
- Fit to m_T, electron E_T, E_{Tmiss}

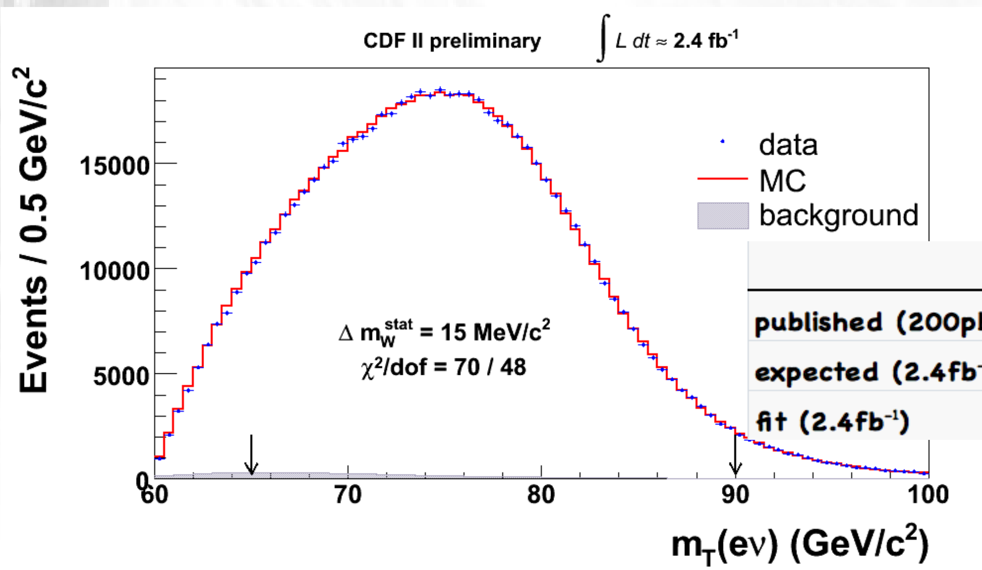


A Tevatron “Legacy” Measurement

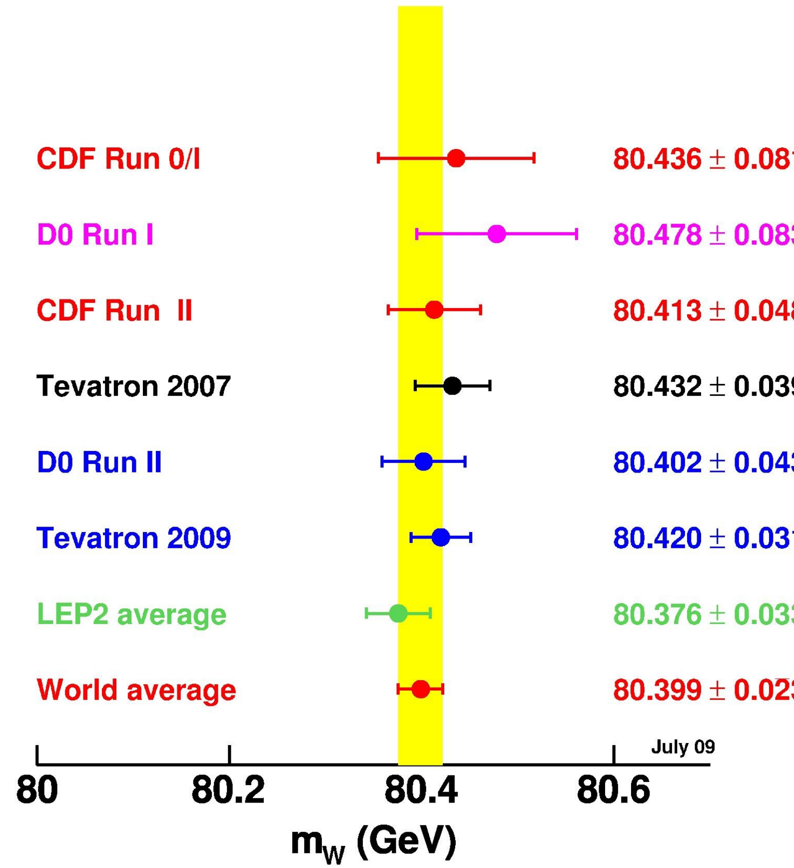
Summer '09: combine D0 1/fb with CDF 200 /pb
$\rightarrow \quad M_W$ = 80.420 +/- 0.031 MeV

Tevatron surpasses LEP!

(arXiv:0908.1374)



	Δm_W^{stat}
published (200pb^{-1})	48 MeV/c^2
expected (2.4fb^{-1})	14 MeV/c^2
fit (2.4fb^{-1})	15 MeV/c^2



- In the works:
  - 2.4 /fb from CDF
  - 4.4 /fb from D0

Medium term: error < 25 MeV
Long term: error ~ theory limit

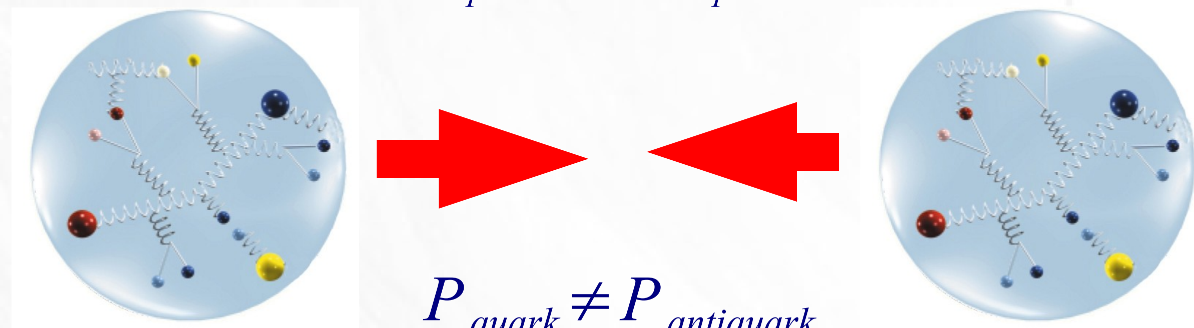
Theory Errors: Intro to PDFs

~~Portable Document Format~~

~~Probability Density Function~~

PDF → Parton Distribution Function

$P_{proton} = P_{antiproton}$



$P_{quark} \neq P_{antiquark}$

- "Partons": the quarks + gluons in the p/pbar
  - W, Z production occurs through *parton collisions (qqbar → W,Z)*

Uncertainty on PDFs

↓

Uncertainty on W eta distribution

↓

Uncertainty on W templates

↓

Uncertainty on W mass

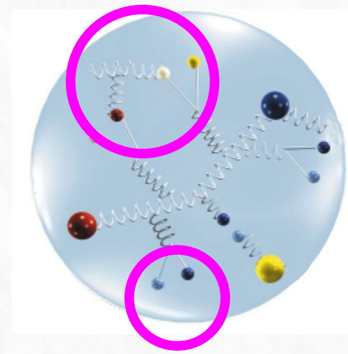
Theory Errors: Intro to PDFs

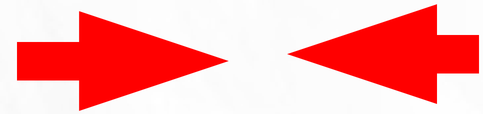
~~Portable Document Format~~

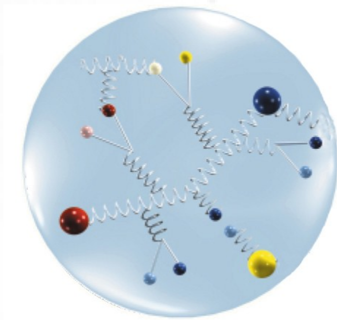
~~Probability Density Function~~

PDF → Parton Distribution Function

$P_{proton} = P_{antiproton}$







$P_{quark} \neq P_{antiquark}$

- "Partons": the quarks + gluons in the p/pbar
  - W, Z production occurs through *parton collisions (qqbar → W,Z)*
- At LHC: W, Z primarily from sea quarks

Uncertainty on PDFs

↓

Uncertainty on W eta distribution

↓

Uncertainty on W templates

↓

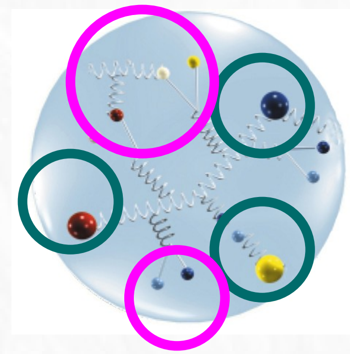
Uncertainty on W mass

Theory Errors: Intro to PDFs

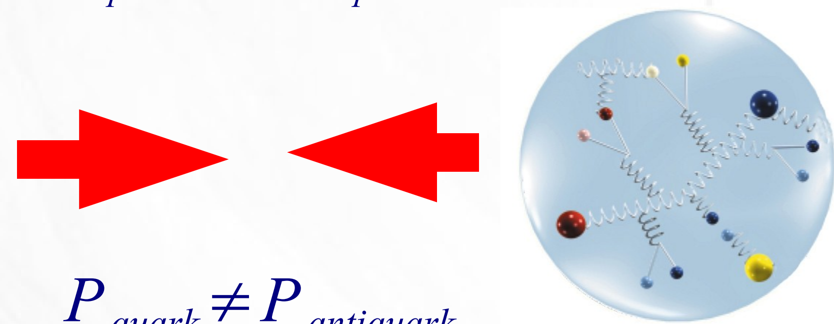
~~Portable Document Format~~

~~Probability Density Function~~

PDF → Parton Distribution Function



$$P_{proton} = P_{antiproton}$$



$$P_{quark} \neq P_{antiquark}$$

- "Partons": the quarks + gluons in the p/pbar
  - W, Z production occurs through *parton collisions (qqbar → W,Z)*
- At LHC: W, Z primarily from sea quarks
- At Tevatron: W, Z primarily from valence quarks

Uncertainty on PDFs

↓

Uncertainty on W eta distribution

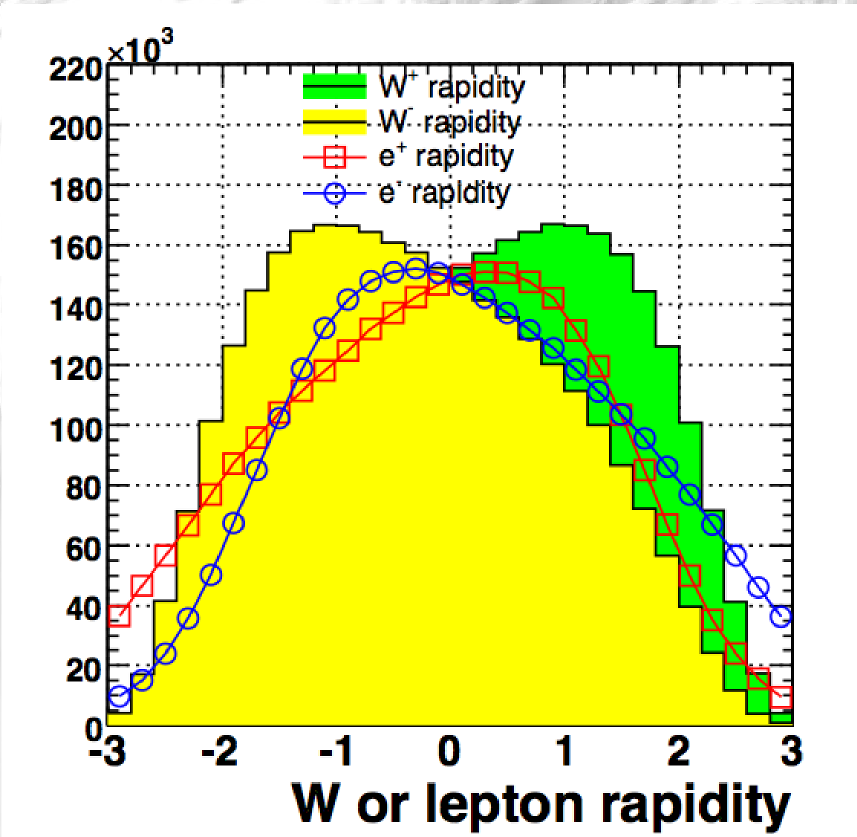
↓

Uncertainty on W templates

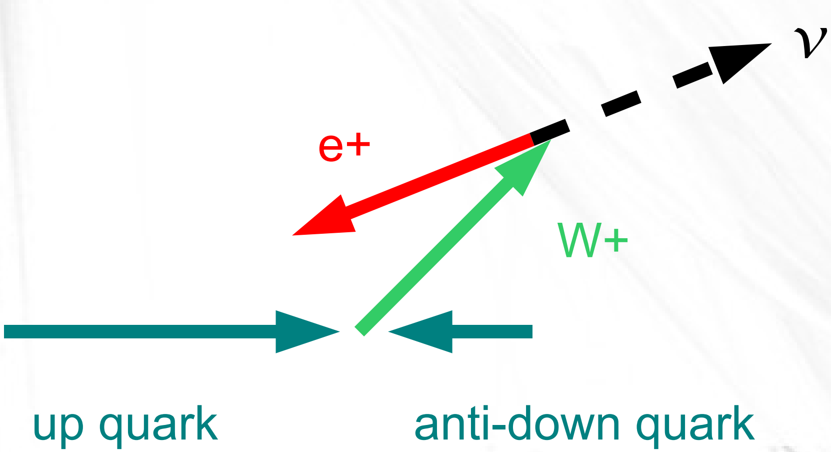
↓

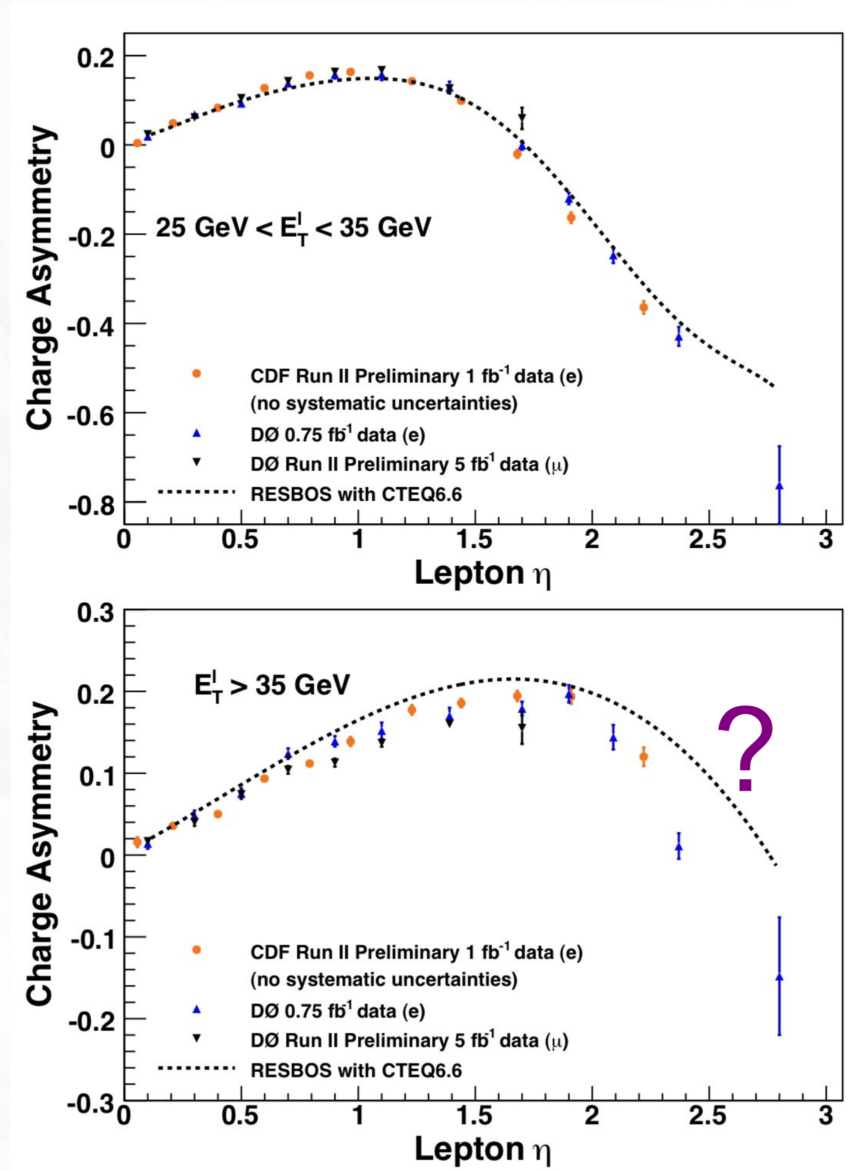
Uncertainty on W mass

W+/W- Asymmetry

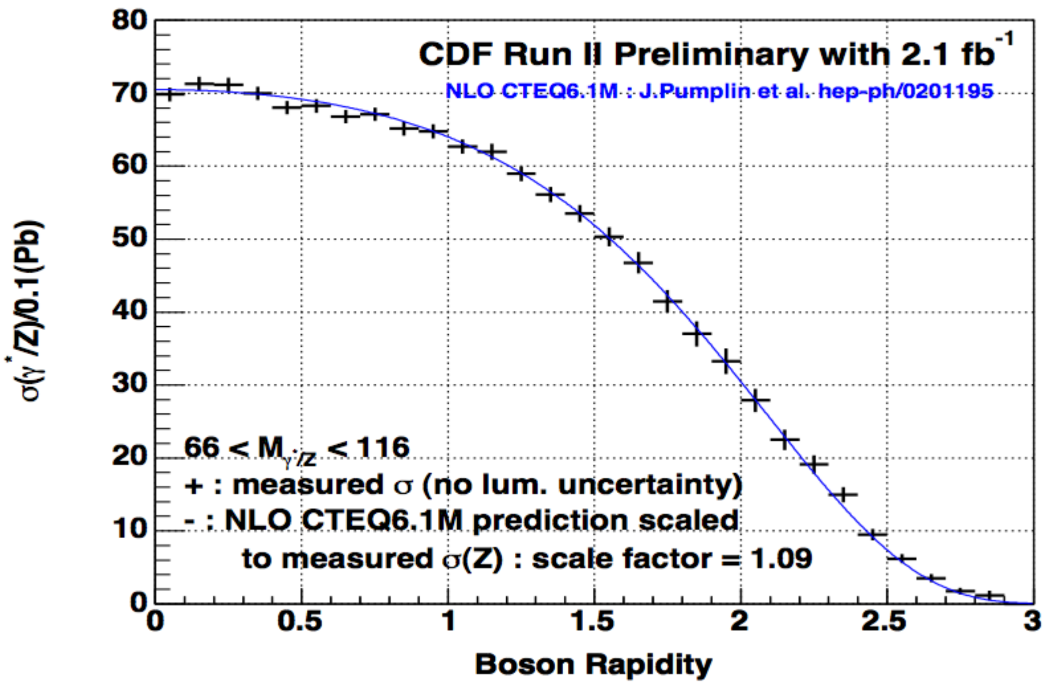


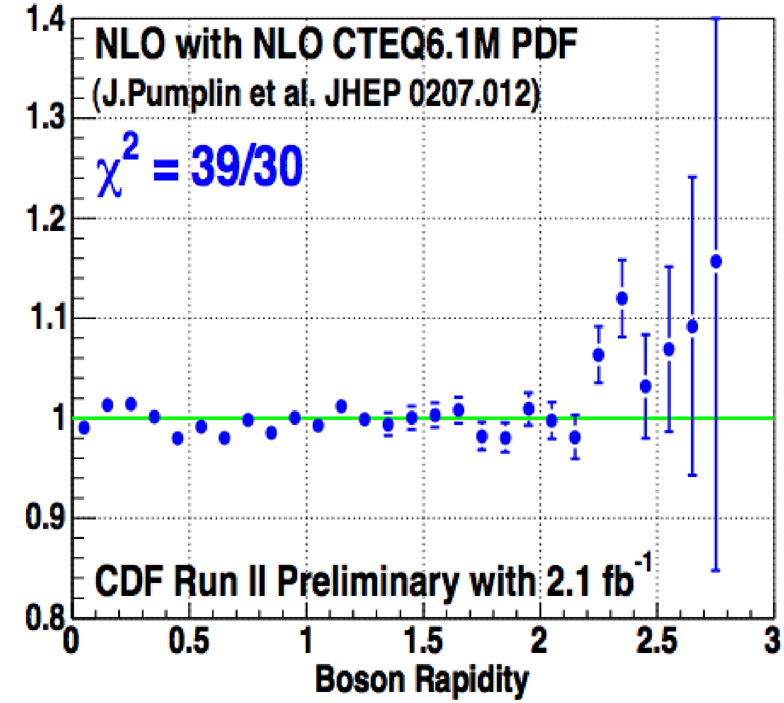
$$< p_{up} > \;\; > \;\; < p_{down} >$$

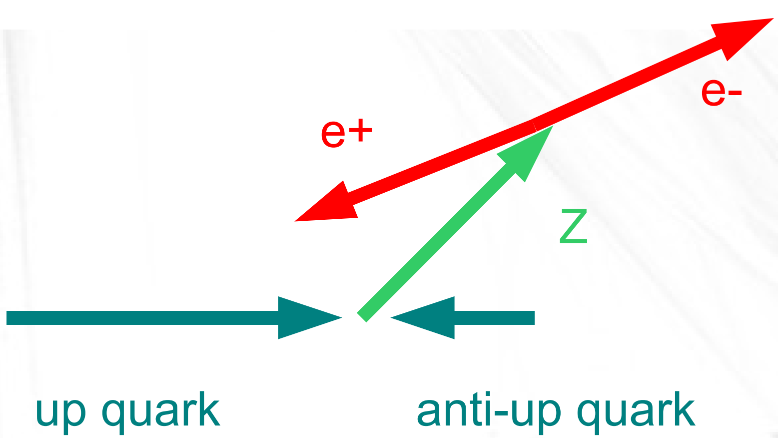




Z Rapidity







- Can fully reconstruct rapidity of Z → ll
- Good agreement seen between theory and experiment w/ CDF measurement
- Used in latest available PDFs

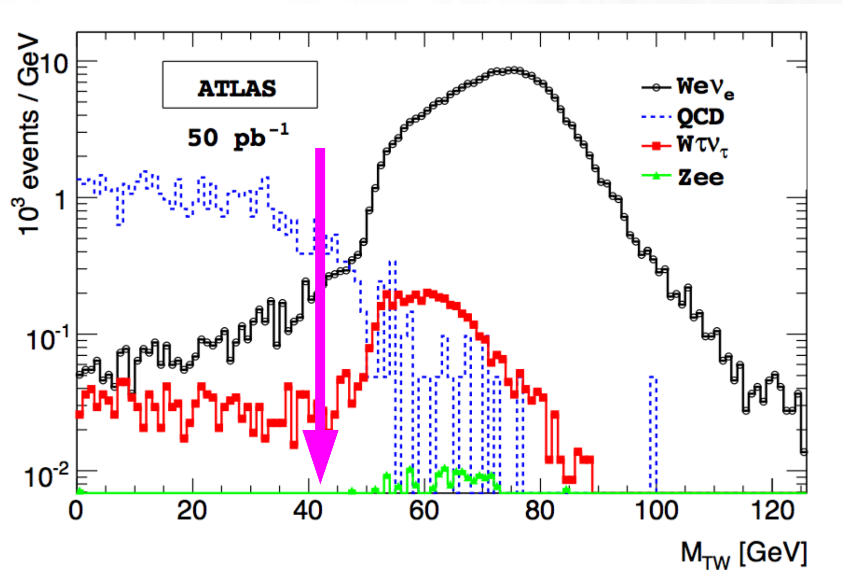
W Mass at LHC

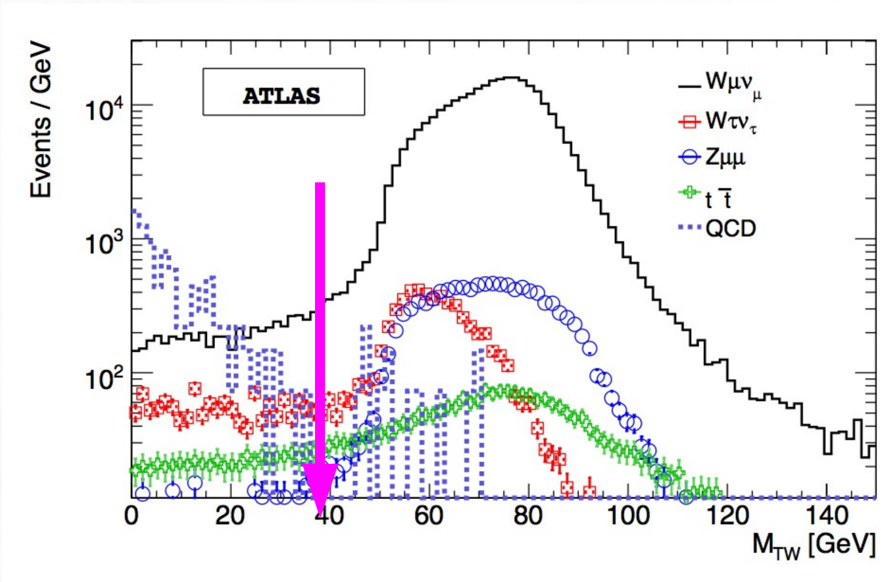
- LHC has the potential to be competitive with Tevatron
- Statistics will not be an issue...
  - 30M W events in 10/fb → 2 MeV effect!
- ...but systematics will
  - Need to understand the detectors (energy calibration, etc.)
  - At LHC energies, PDFs less well understood
    → 20-25 MeV effect
- What work needs to be done?

First, let's find the W...

Observing the W

50 /pb (~100 /pb at 7 TeV) → data this year

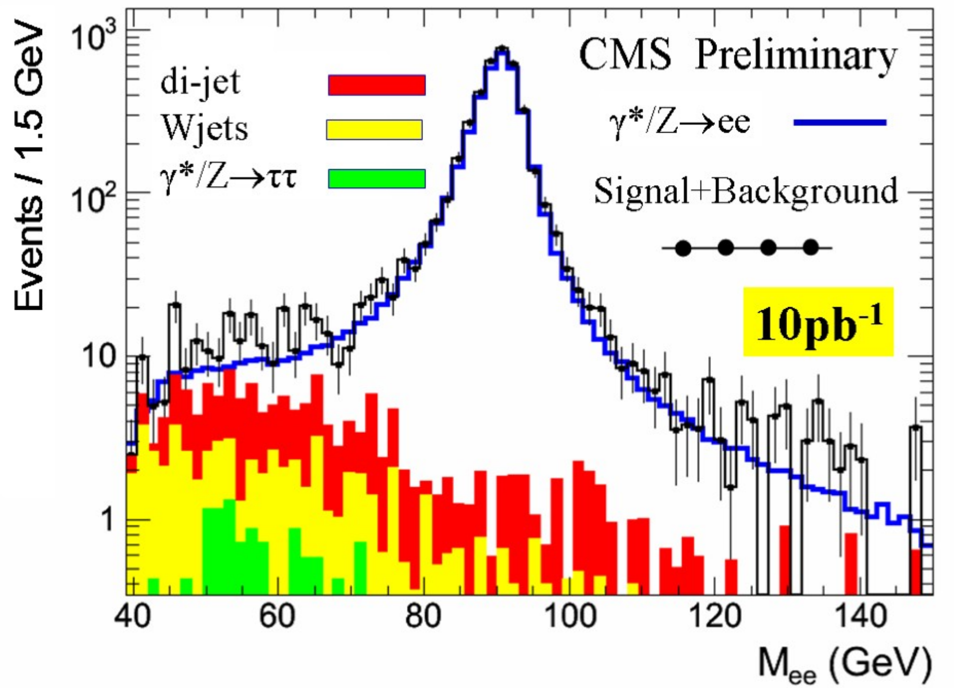


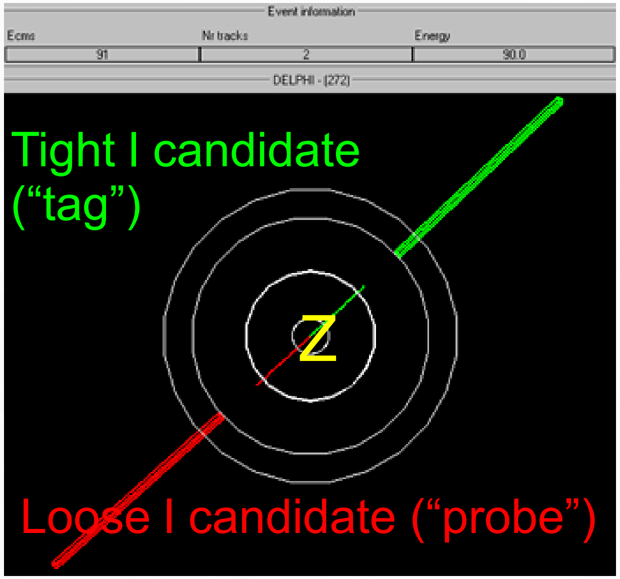


	# signal (10k)	# bkgnd (10k)	Pred. (nb)
W → ev	22.67 +/- 0.04	0.61 +/- 0.92	20.52 +/-0.04 +/-1.06
W → mu v	30.04 +/- 0.05	2.01 +/- 0.12	20.53 +/- 0.04 +/- 0.63

- Good early measurement: low background, simple cuts, robust
- 1 /fb, theory becomes limiting factor on cross section
- Luminosity standard candle?

Observing the Z



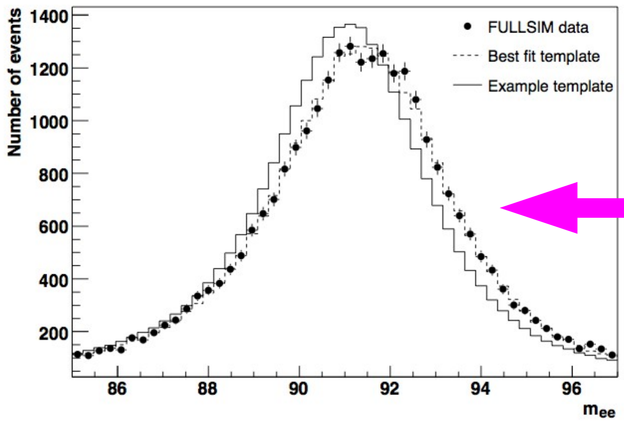


- *Z is extremely useful for early calibrations*
  - Easily observe Z with ~10 pb
  - Eventually can go from 1 to 0.02% uncertainty on tracker momentum resolution, scale, 10 to 1% uncertainty on calorimeter energy resolution!
  - Very little background → can calculate lepton tagging efficiencies

W Mass at the LHC

10 /fb

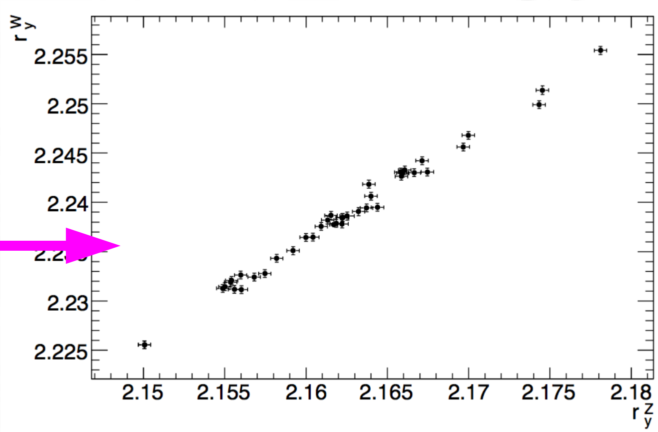
3.5M Z's



SOURCE	PREDICTED ERR (MeV)
Statistics	2
Energy scale	4
Energy resolution	1
Lepton efficiency	4.5(e), <1(mu)
Recoil	5
Background	1.5
PDFs	1
W width	1
W pt	1
QED	<1
Total	8(e), 7(mu)

40M W's

W, Z rapidity highly correlated



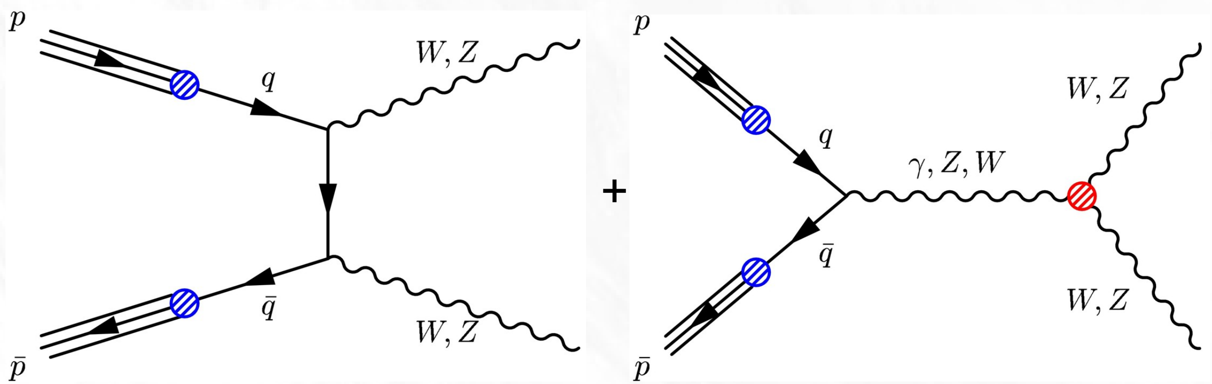
(i.e., Z will tell you about W PDFs)

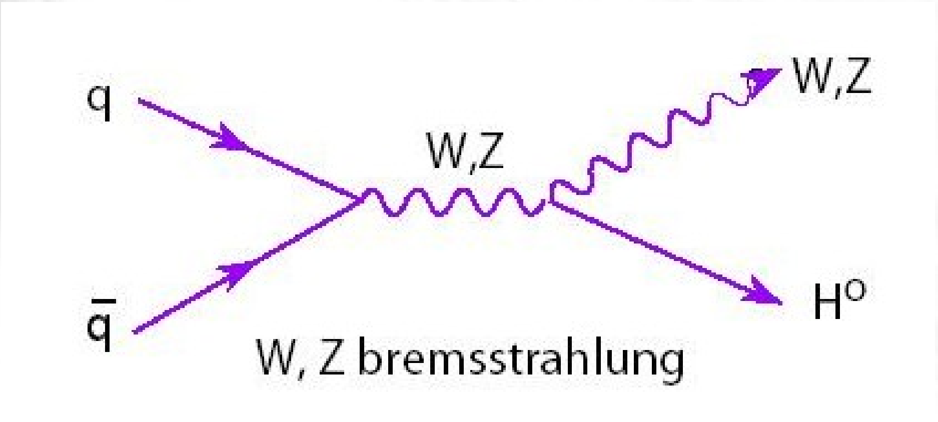
Cuts assumed:
Lepton Pt > 20 GeV
Etmiss > 20 GeV
|eta| < 2.5
Recoil < 30 GeV

"Reevaluation of the LHC potential for the measurement of M_W"
Eur. Phys. J. C57:627-651, 2008

Two Reasons to Study Two Bosons

- Can be studied as indirect evidence of NP (New Physics)
- Cross-sections and decay signatures not unlike that of the light Higgs

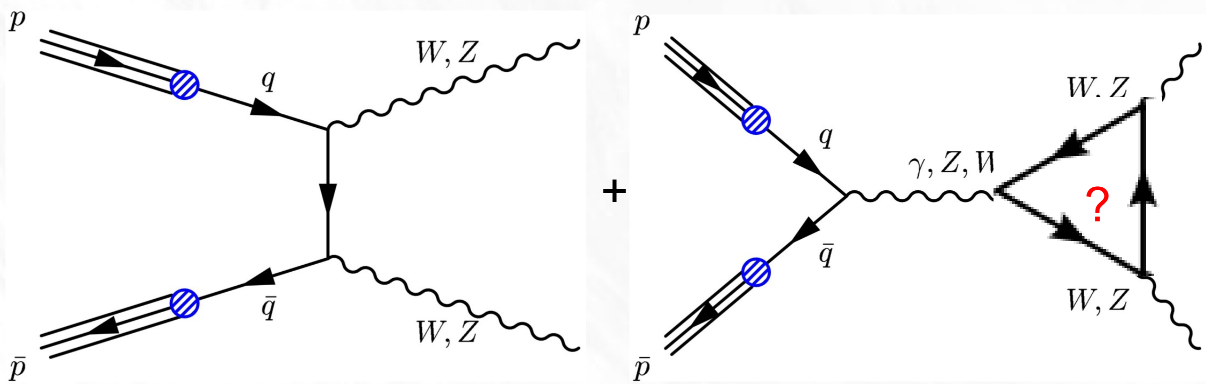




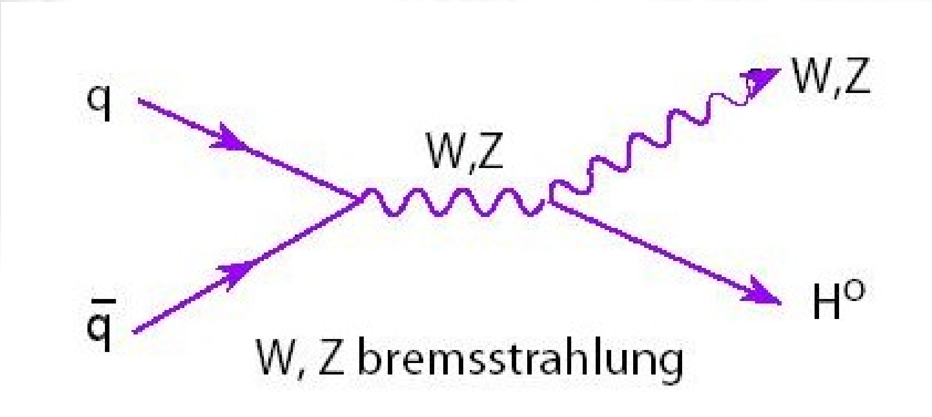
$H \rightarrow bb \quad \leftrightarrow \quad W/Z \rightarrow qq$
$H \rightarrow bb \quad \leftrightarrow \quad Z \rightarrow bb$

Two Reasons to Study Two Bosons

- Can be studied as indirect evidence of NP (New Physics)
- Cross-sections and decay signatures not unlike that of the light Higgs

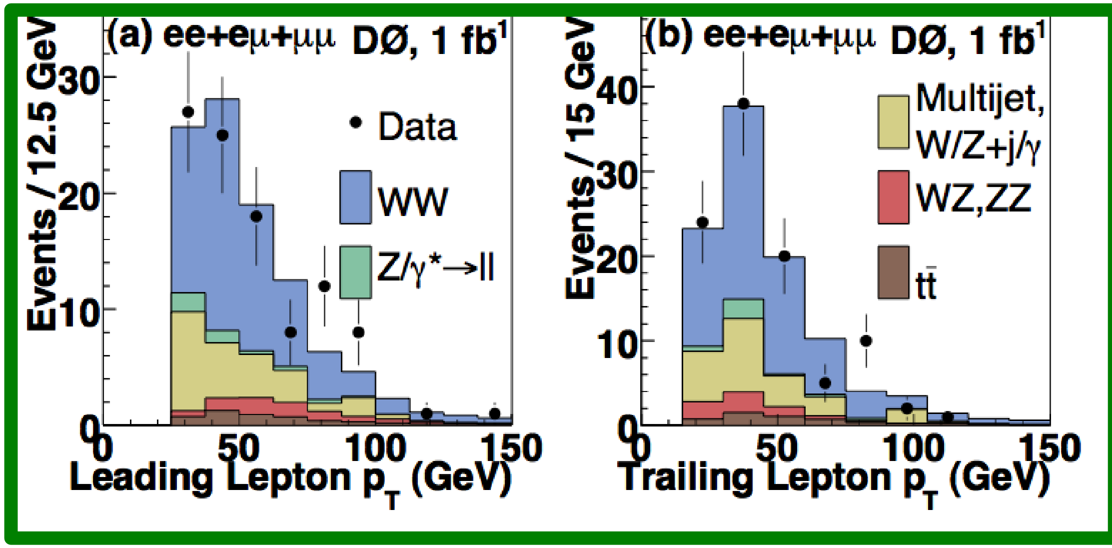


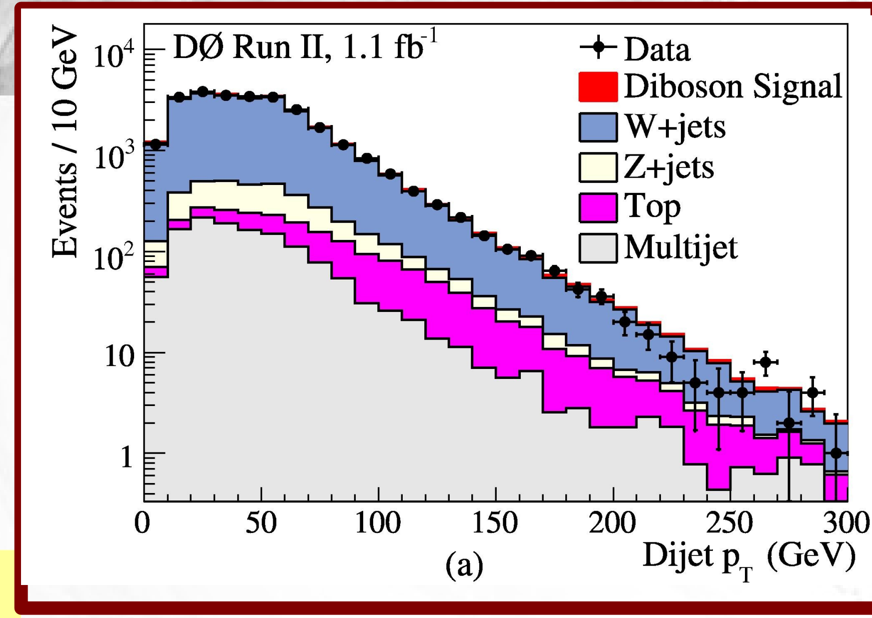
"Anomalous Triple Gauge Coupings"



$H \rightarrow bb \quad \leftrightarrow \quad W/Z \rightarrow qq$

$H \rightarrow bb \quad \leftrightarrow \quad Z \rightarrow bb$

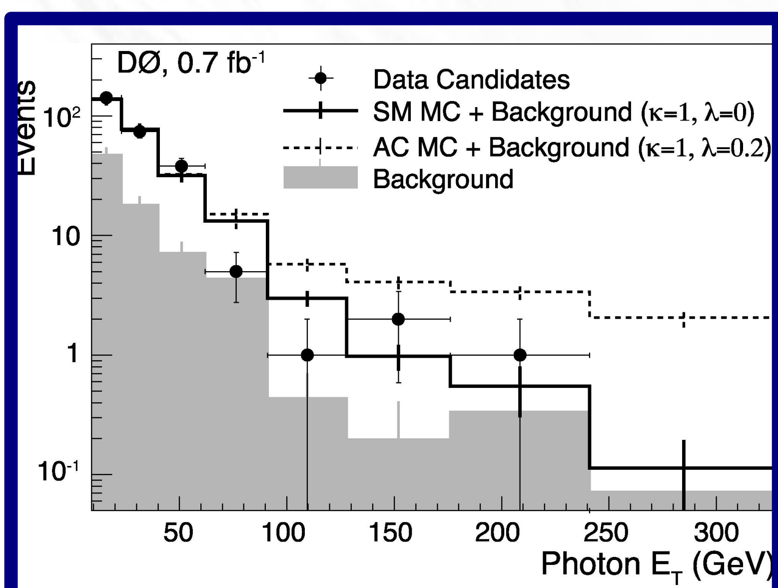


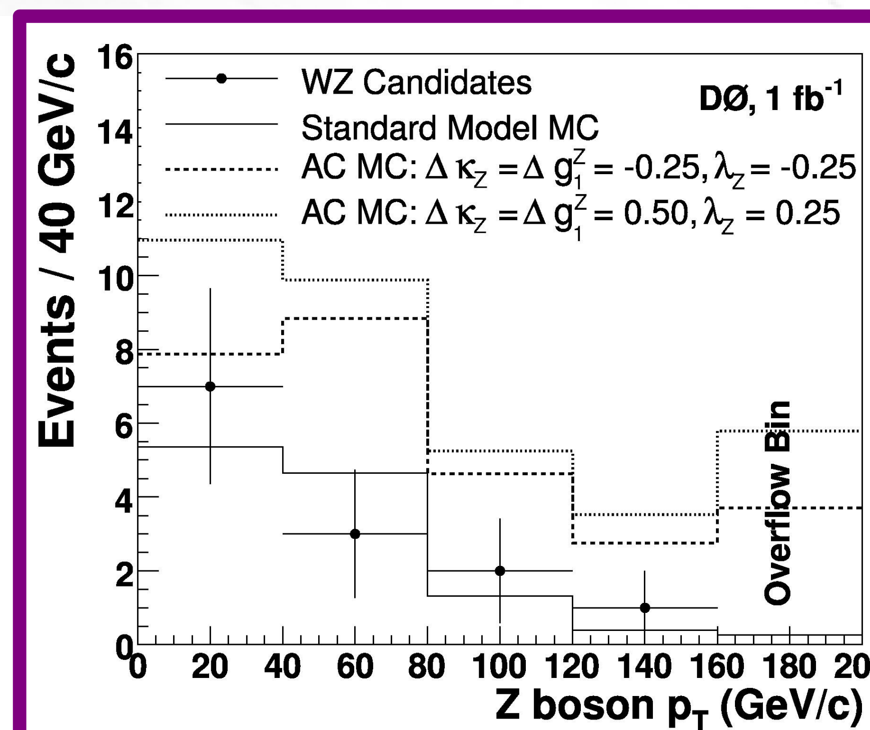


Process	Sensitive to	Discrim. Var	Data
$W\gamma \to l\nu\gamma$	$WW\gamma$	Photon Et	0.7 /fb
$WV \to l\nu jj$	$WW\gamma, WWZ$	W/Z->jj Pt	1.1 /fb
$WW \to l\nu l\nu$	$WW\gamma, WWZ$	Lepton Ets	1 /fb
$WZ \to l\nu ll$	WWZ	Z->ll Pt	1 /fb

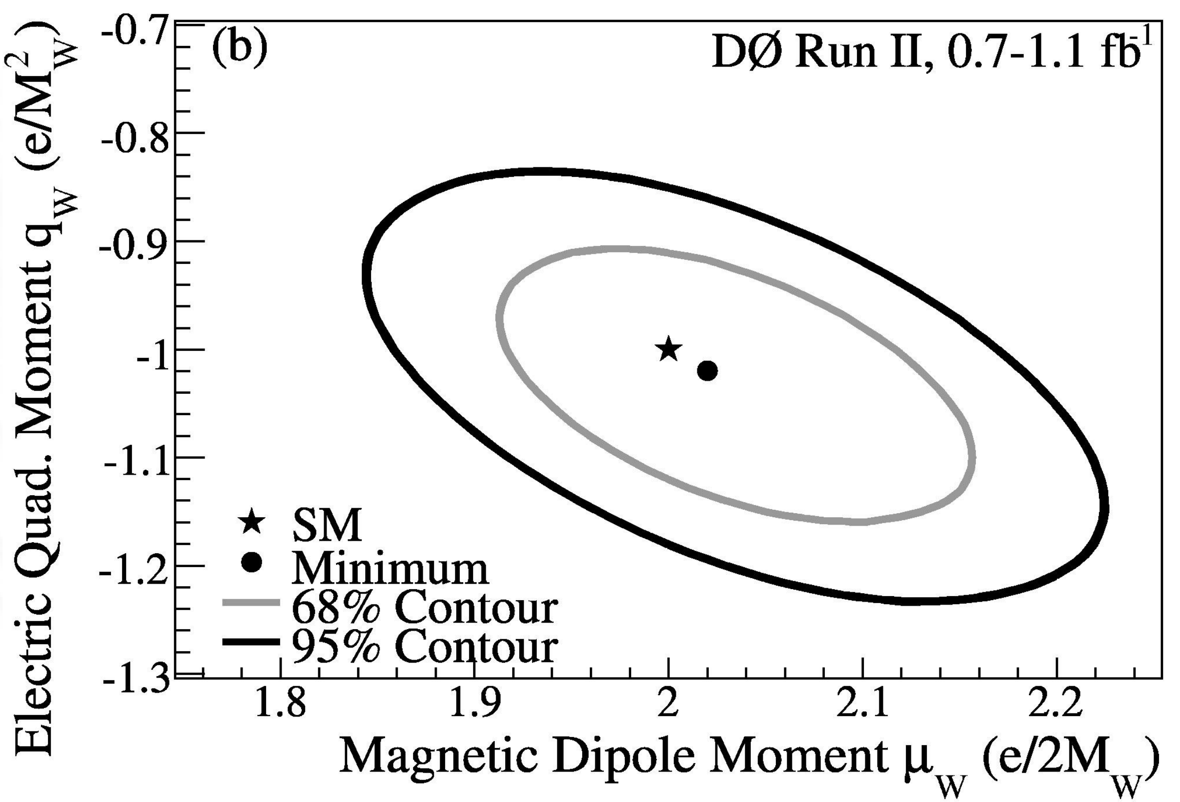
arXiv:/0907.4952

D0 Studies:
Charged triple gauge couplings



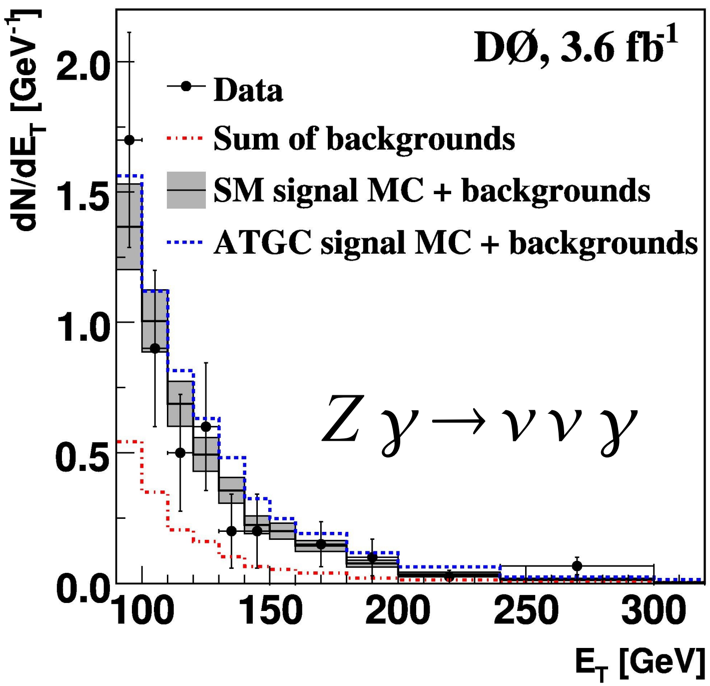


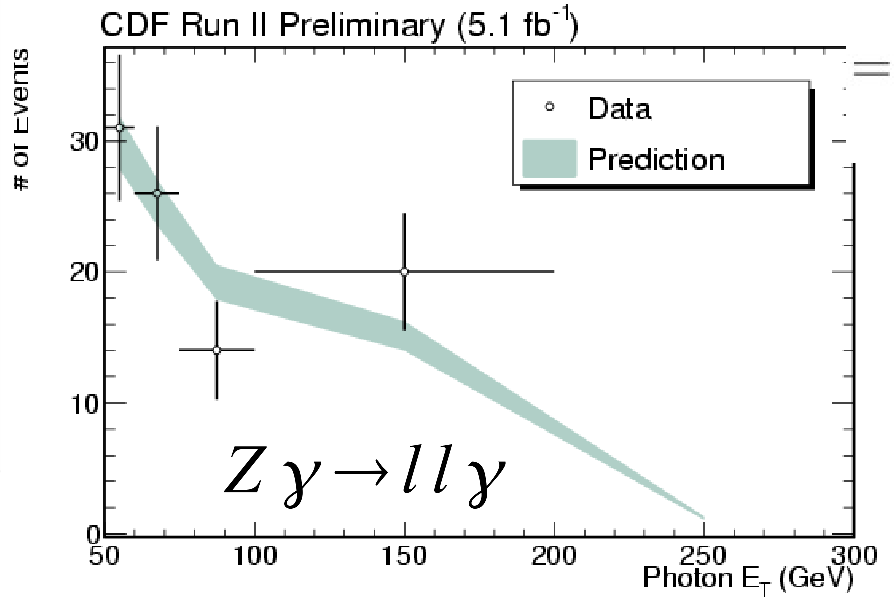
The Result



- Could be competitive with LEP if combined w/ CDF at current amount of data

$Z\gamma\gamma$, $ZZ\gamma$ TGC



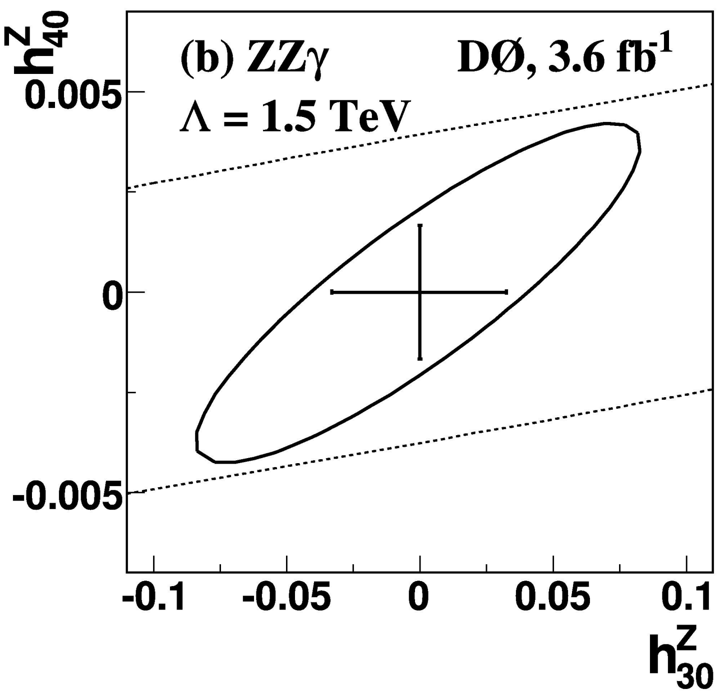


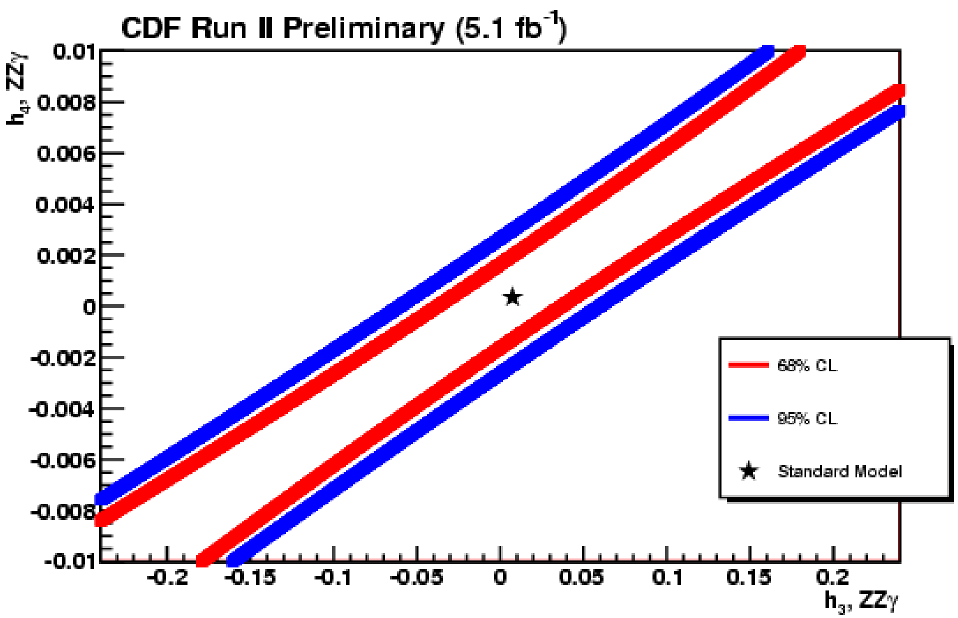
E DIPOLE MOMENT

$$= \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}(h_3^Z - h_4^Z)$$

B QUADRUPOLE MOMENT

$$= \frac{2\sqrt{10}e}{m_Z^2}h_3^Z$$



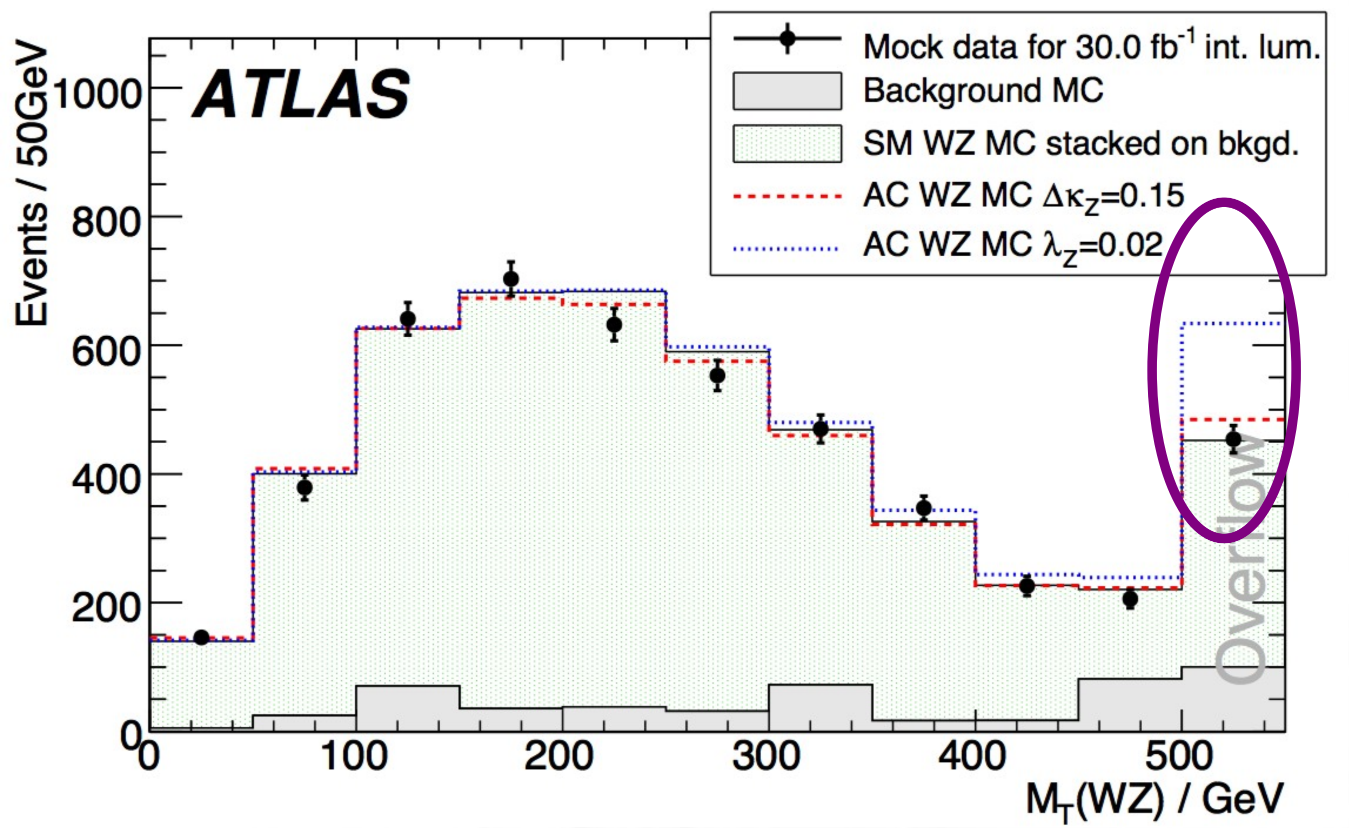


Phys. Rev. Lett. 102, 201802 (2009)

TGC at the LHC

- Three advantages over Tevatron
  - Higher diboson cross sections
  - Higher energy → new physics manifests itself here
  - Higher luminosity (next couple of years...)

30 /fb



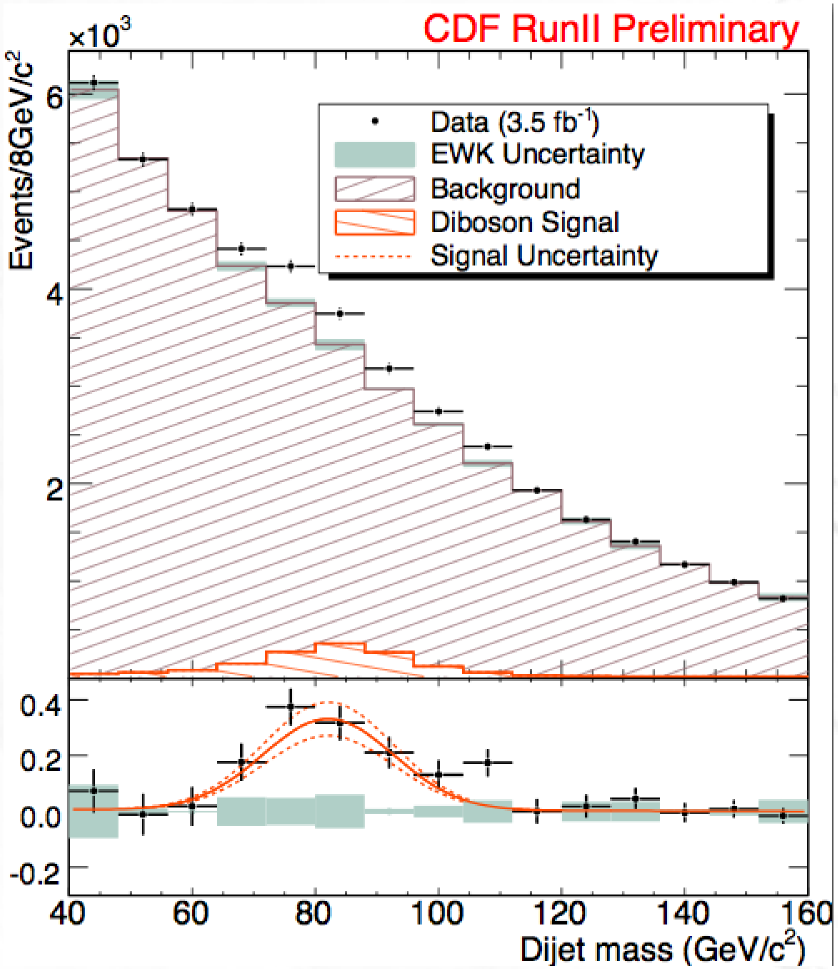
WZ:
Highest energy where the action's at!

cf. CDF, 1.9 /fb : $\Delta\kappa_Z \in (-1.09, 1.40),\ \lambda_Z \in (-0.18, 0.18)$

A First Step Into W/Z → Jets

- The first "light Higgs analog" observation
  - WW/WZ/ZZ → E_{Tmiss} + jets
- Tricky – MUCH more background than W/Z → leptons!
- Tevatron performance + innovative techniques

5.3 σ (p = 1.2e-7)
→ Observation!



Event Type	# Events Fitted
Electroweak (bkgnd)	36140 +/- 1230
Non-electroweak	7249 +/- 1130
WW+WZ+ZZ	1516 +/- 239

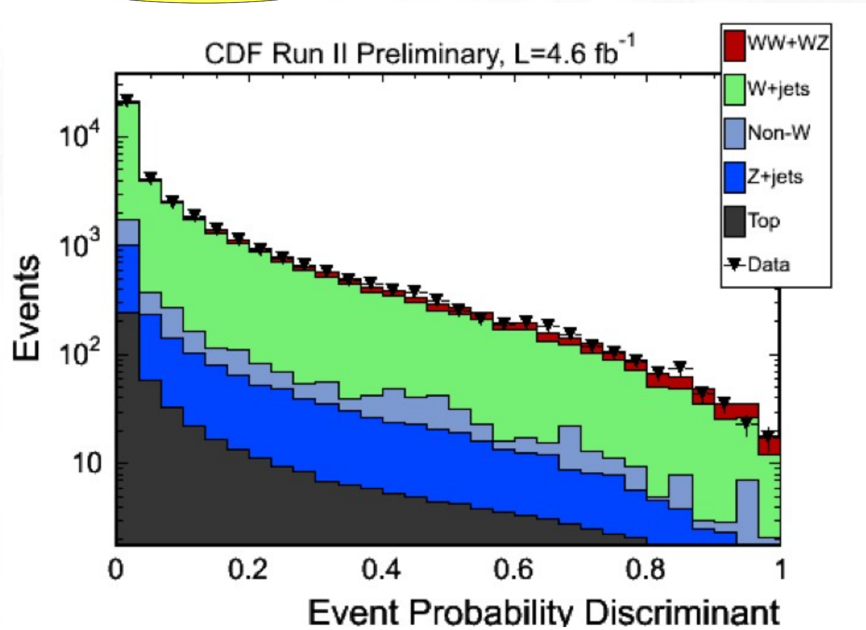
Measured xsec = 18 +/- 3.8 pb
(SM prediction = 16.8 +/- 0.5 pb)

PAPER REFERENCE

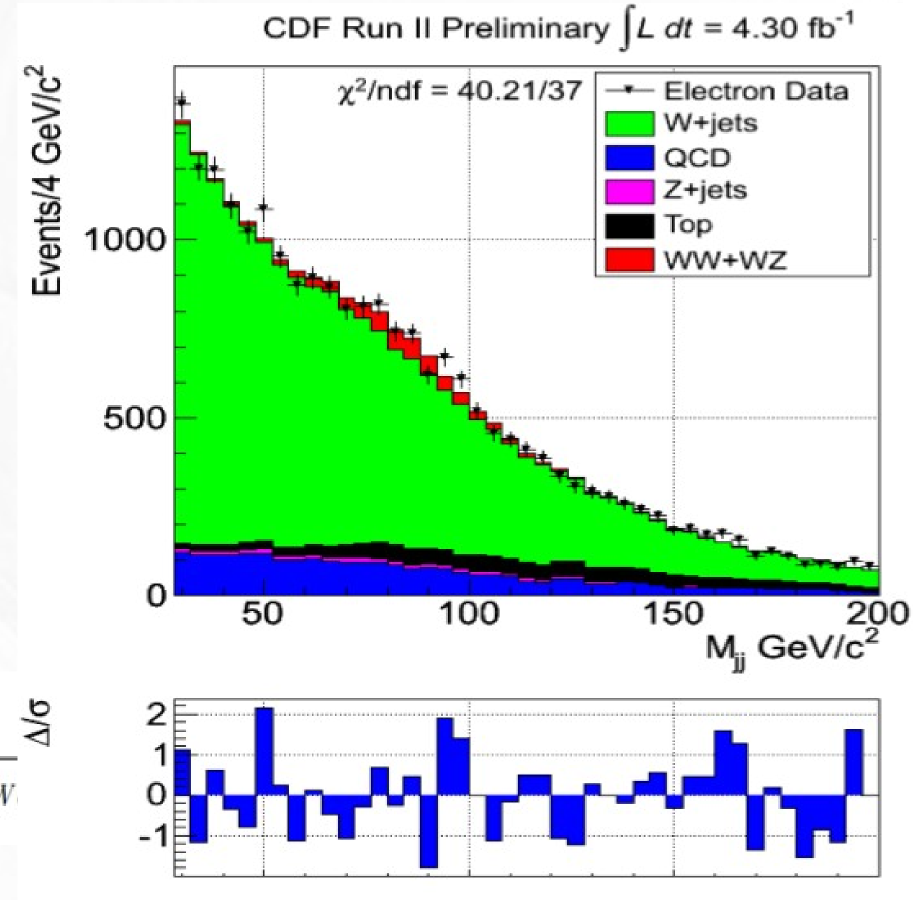
...And Another Step

$5.6\,\sigma$
→ Observation!

$5.2\,\sigma$
→ Observation!



$$EPD = \frac{P_{WW} + P_{WZ}}{P_{WW} + P_{WZ} + P_{schan} + P_{tchan} + P_{Wjj} + P_{Wgj} + P_{Wbb} + P_{W}}$$



Measured xsec = 16.6 +3.5 -3.0 pb
(SM predicted = 15.1 +/- 0.8 pb)

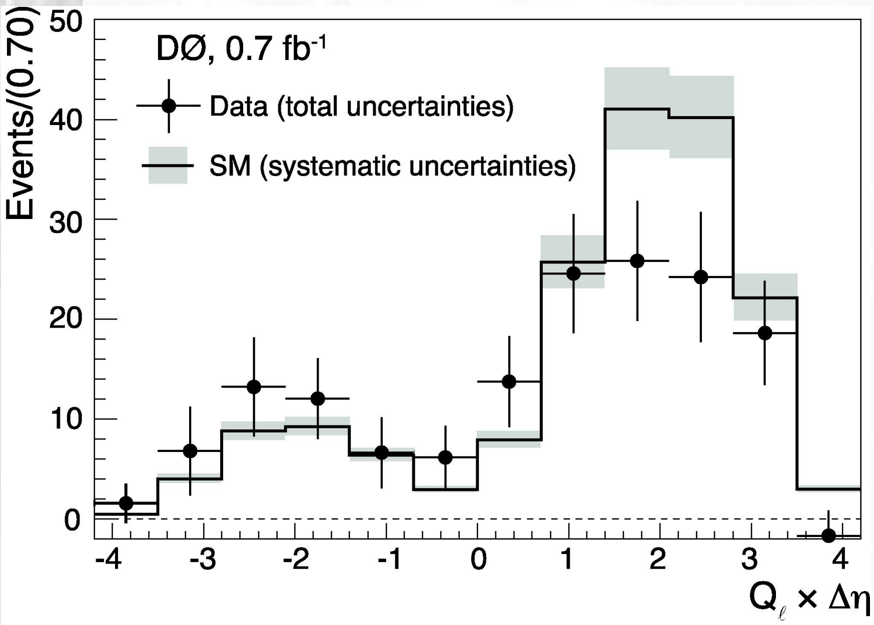
Measured xsec = 18.1 +/- 4.3 pb

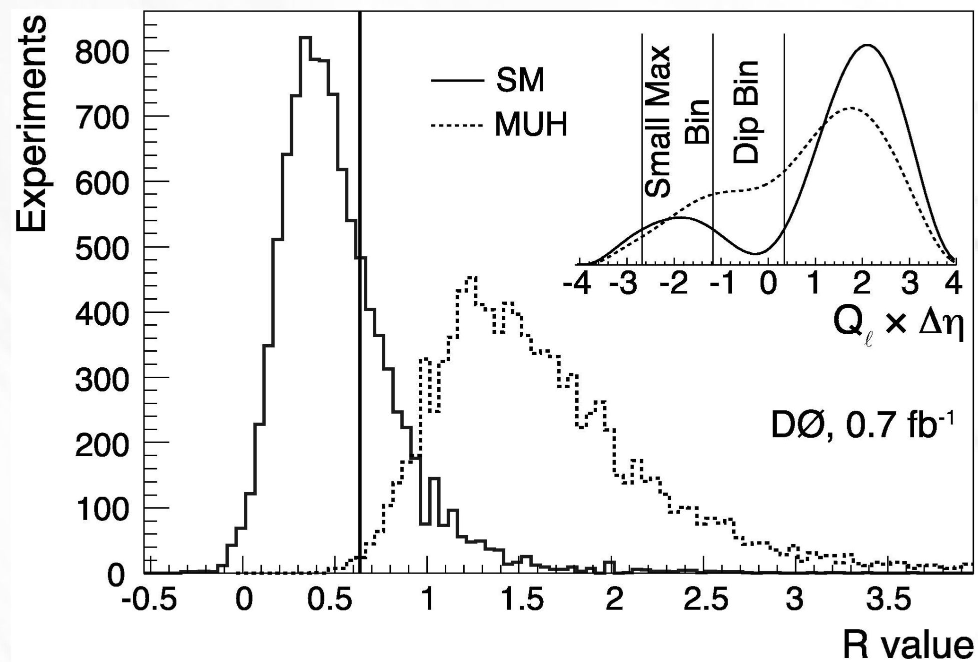
- Two observations of WW/WZ → l+ E_{Tmiss} + jj with two observables

Alternate Searches for NP (I)

hep-ex/0803.0030v2

"THE RADIATION ZERO"

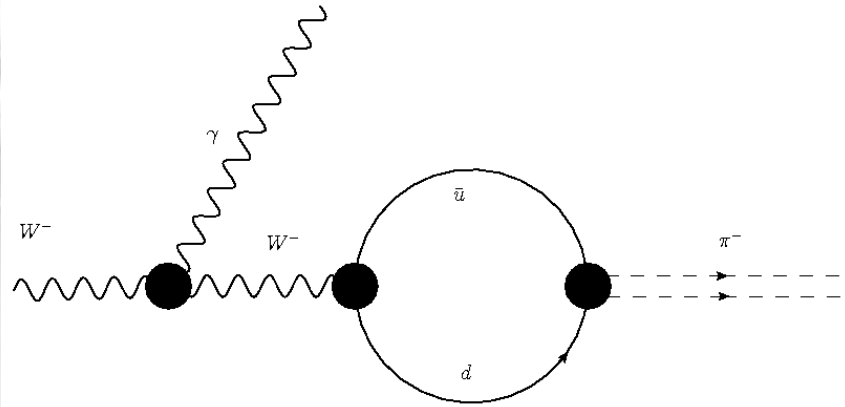




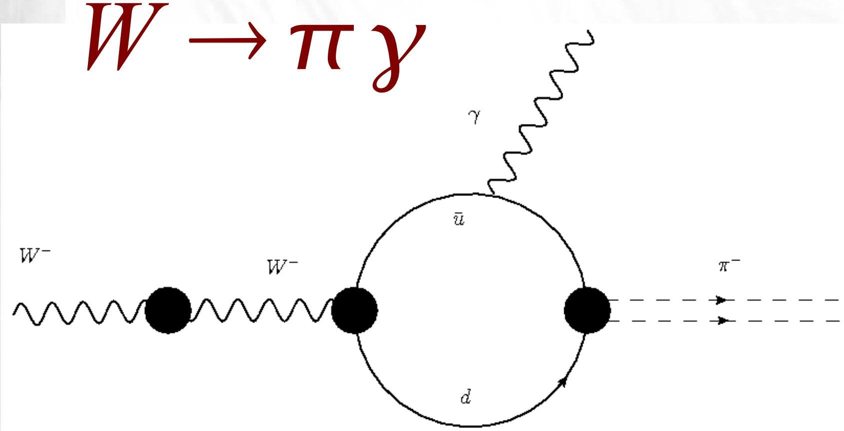
- For product of charge and eta difference between W and gamma, expect dip about 0 in SM
- "MUH" - Minimal Unimodal Hypothesis – has W with no magnetic dipole moment

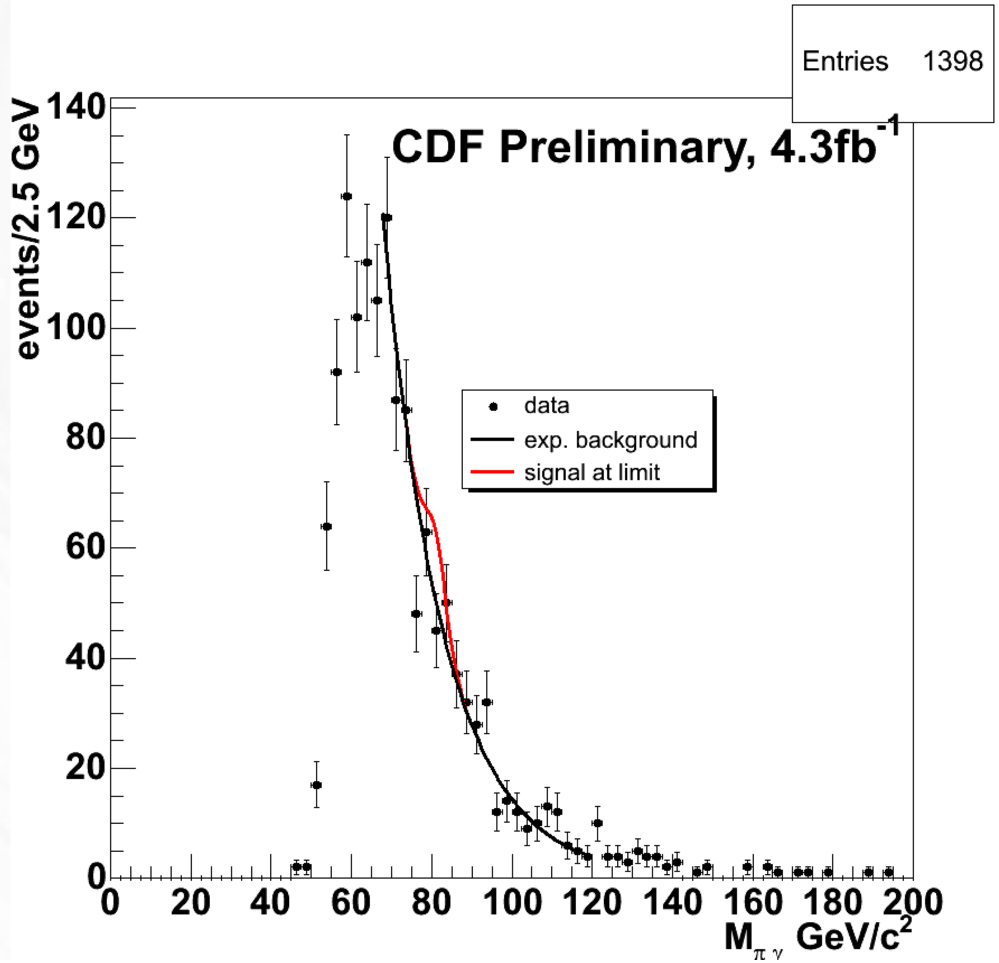
Alternate Searches for NP (II)

- NP behind production of a photon and a pion?



$W \to \pi\gamma$





BR(W->$\pi\gamma$)/BR(W->eν) < 6.4 x 10^{-5} at 95% confidence

Conclusions

- A physical phenomena that affects every particle* is bound to be a broad topic – I've given you a snapshot of it in the context of turn-of-the-decade hadron collider physics
- Going forward
  - Will be interesting to see how precisely the W mass can be measured (↔ how precise the Higgs constraint can be)
  - Will NP be discovered first as an indirect loop phenomenon?
  - Take it away, LHC...

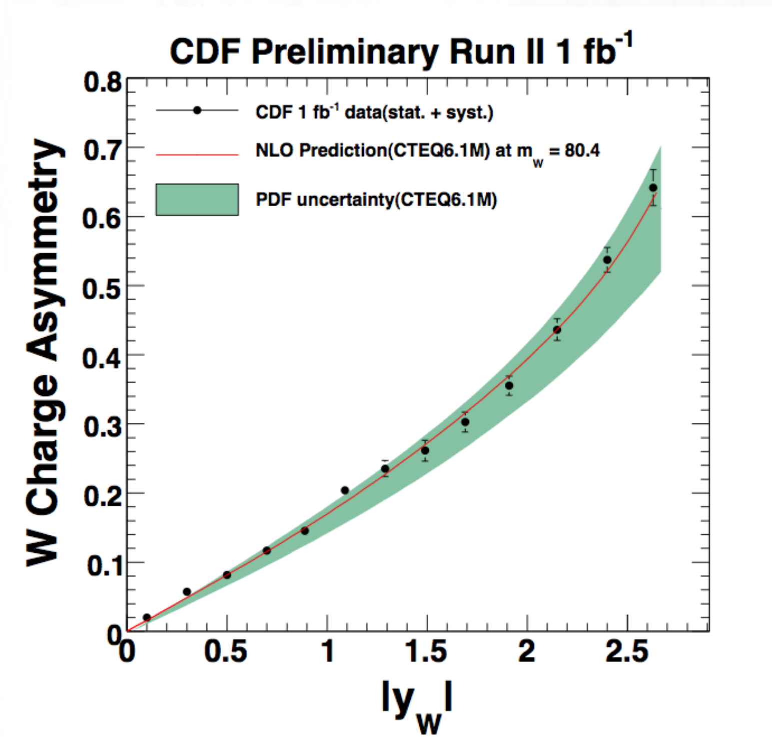
*except the gluon

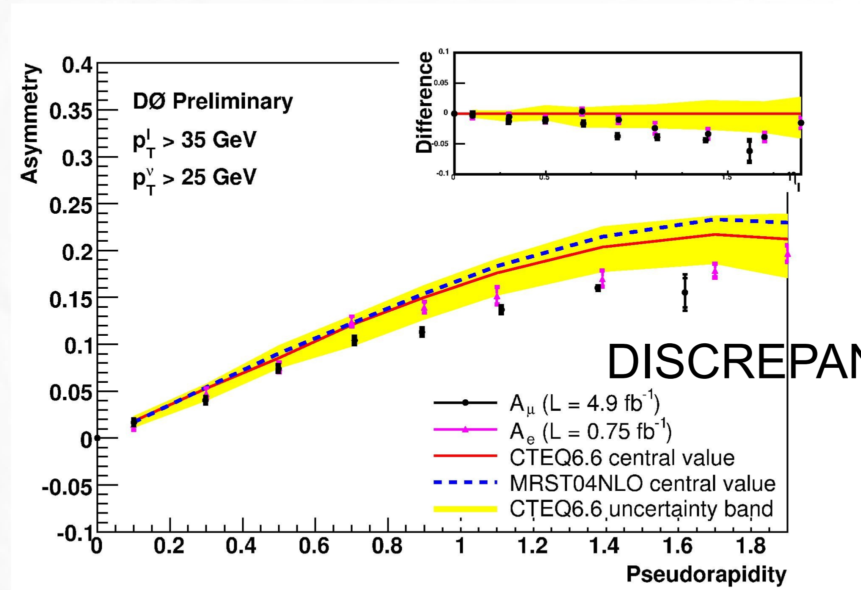
BACKUPS

W Forward-Backward Asymmetry

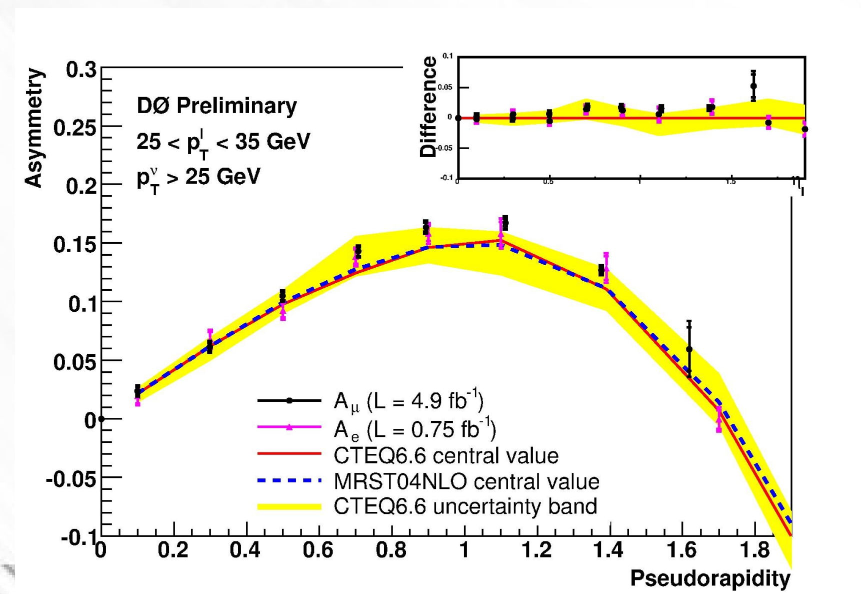
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

- U carries more momentum than d → W+(-) in direction of u (ubar)

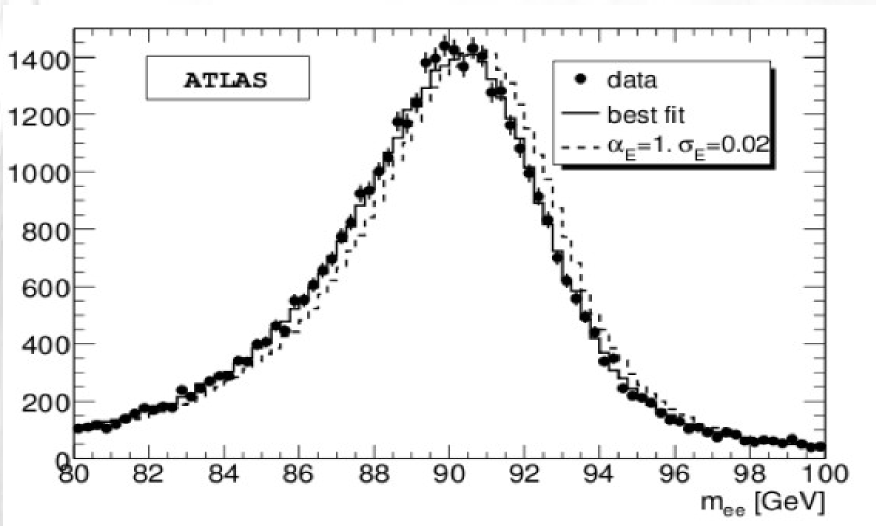


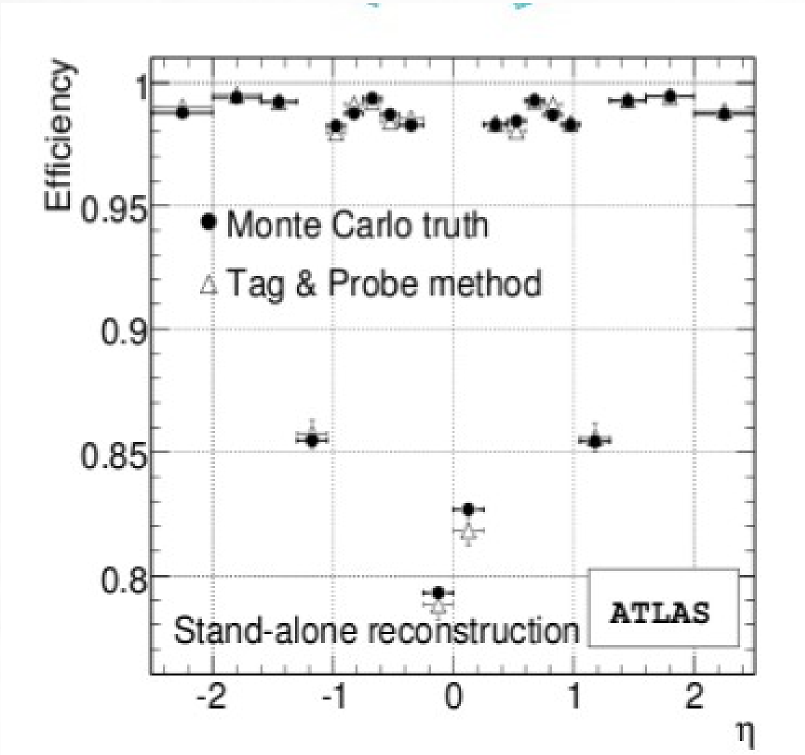


DISCREPANCY!



Plots related to LHC calibration





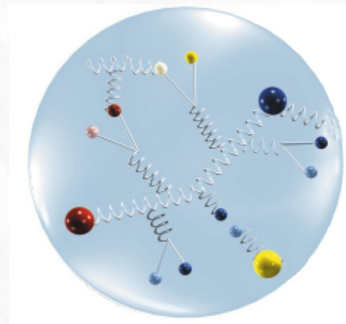
Theory Errors: Intro to PDFs

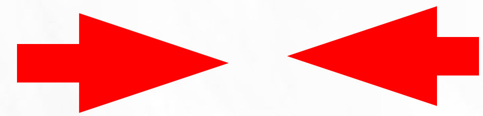
~~Portable Document Format~~

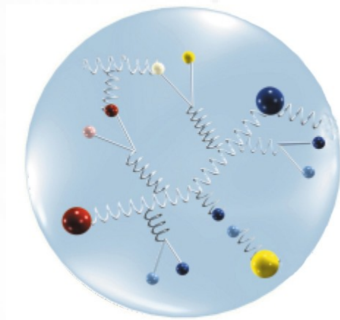
~~Probability Density Function~~

PDF → Parton Distribution Function

$$P_{proton} = P_{antiproton}$$







$$P_{quark} \neq P_{antiquark}$$

- "Partons": the quarks + gluons in the p/pbar
  - W, Z production occurs through *parton collisions (qqbar → W,Z)*
- PDFs model the momenta carried by u, d, g, etc...
- $<P_u> \; > \; <P_d>$ at Tevatron
  - W+ (-) in direction of p (pbar)

Uncertainty on PDFs

↓

Uncertainty on W/Z eta distribution

↓

Uncertainty on W templates

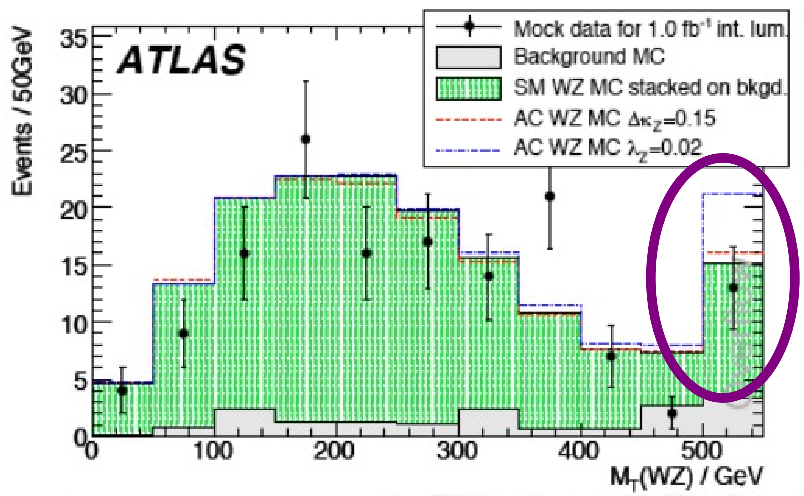
↓

Uncertainty on W mass

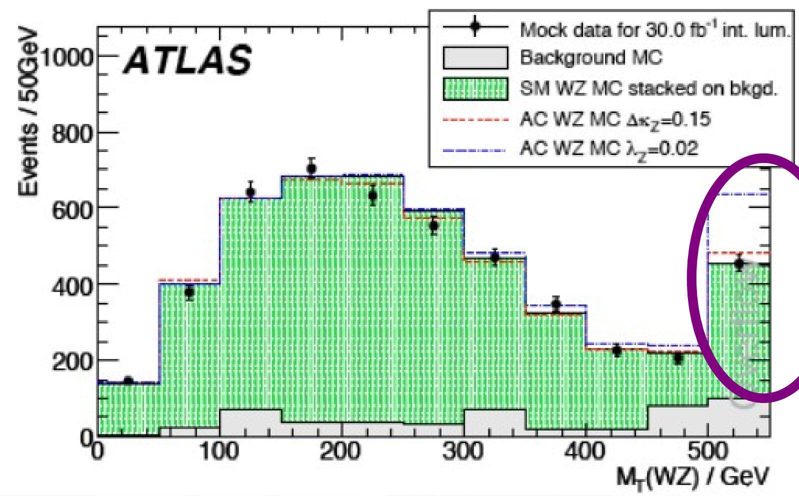
TGC at the LHC

- Three advantages over Tevatron
  - Higher diboson cross sections
  - Higher energy → new physics manifests itself at high M(VV)
  - Higher luminosity (next couple of years...)

End of 2011



2014?



cf. CDF, 1.9 /fb...

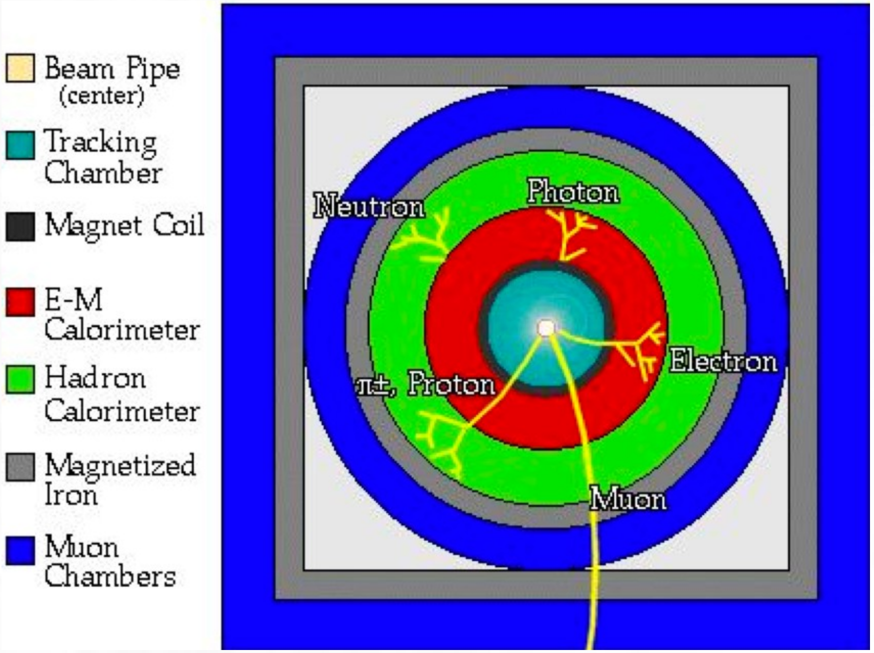
Coupling	Expected Limit w/o Systematics	Expected Limit w/ Systematics	Limit w/o Systematics	Limit w/ Systematics
Δg	(-0.15,0.25)	(-0.16,0.26)	(-0.15,0.26)	(-0.22,0.32)
$\Delta\kappa$	(-0.81,1.09)	(-0.88,1.16)	(-0.72,1.03)	(-1.09,1.40)
λ	(-0.13,0.14)	(-0.14,0.15)	(-0.13,0.14)	(-0.18,0.18)

Table: WZ Results for $\Lambda = 1.5$ TeV

http://www-cdf.

Detecting Particles: A Primer

ALL DETECTORS RELEVANT TO THIS TALK ARE BUILT ON THESE PRINCIPLES



System	Good for	Reason	Made of
Tracking	Charged particle momenta	Track curvature in B-field	Silicon pixels/strips, wires
Electromagnetic calorimeter	electron/photon energies	Bremsstrahlung (e), pair production (g)	Scintillator, possibly absorber
Hadronic calorimeter	Hadrons	Nuclear interaction	Scintillator+absorber
Muon	Muons	The muon can make it there	Absorber, wires